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17. Abstract

Probabilistic models were developed for the estimation of global and local ice for fixed marine structures. The models produce load descriptions which are compatible with probability-based design code requirements and can thus be used in selecting design criteria. Ice loading is estimated by using probabilistic environmental inputs in appropriate ice-structure interaction models to produce a probabilistic distribution of the load. This is then used in extremal models to calculate the probability distribution of the maximum annual load or pressure which is the basis for selecting design loads. The study included the statistical analysis of environmental data and ice mechanical properties in order to obtain the best probabilistic descriptors of input parameters to the model. Ice-structure interaction models were selected from available approaches and new models were developed areal ice feature collisions in open water and winter conditions. The probabilistic models were developed include stochastic process models for different ice load scenarios, models for the exposure levels of the structure to a given scenario and models for estimating the load magnitude during each interaction event. Extremal models for the discrete Poisson process and for stationary continuous processes are also used. These components were included in integrated models and computer programs for calculating global loads and local pressures and techniques for dealing with short data records were also developed. This volume gives a detailed description of the study.

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17. Résumé

Des modèles probabilistes ont été construits pour l'estimation des charges globales et locales de la glace auxquelles sont exposées les structures fixes en mer. Ces modèles produisent des descriptions de la charge qui sont compatibles avec les exigences des codes de conception reposant sur les probabilités et ils peuvent donc Oetre utilisés pour la détermination des critères de conception. On estime la charge de la galce en introduisant des données environnementales probabilistes dans les modèles appropriés de l'interaction glacestructure afin d'obtenir une distribution probabiliste de la charge. On utilise ensuite cette distribution dans des modèles extrêmaux pour calculer la distribution des probabilités de la charge, ou pression, annuelle macimale éa partir de laquelle sont déterminées les charges théoriques. L'étude a comporté des analyses statistiques des données environnementales et des propriétés mécanique de la glace pour la détermination des meilleurs descripteurs probabilistes des paramètres d'entrée du modèle. On a choisi des modèles d'interaction galcestructure à partir d'approches disponibles et on a élaboré de nouveaux modèles pour les collisions avec la glace dans une zone en eau libre et en hiver. Les modèles probabilistes construits comprennent des modèles de processus stochastiques pour différents scénarios quant à la charge de la glace, des modèles pour le niveaux d'exposition de la structure à un scénasrio donné et des modèles pour l'estimation de l'importance de la charge durant chaque interaction glace-structure. Des modèles extrêmaux pour le processus discret de Poisson et pour des processus continus stationnaires sont également utilisés. Ces composantes ont été introduites dans des modèles intégrés et des programmes informatiques pour le calcul des charges globales et des pressions locales. Des techniques ont également été mises au point pour les statistiques couvrant une courte période. Ce volume fournit une description détaillée de l'étude.

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PREFACE

This report is one of several reports on the research work in the field of marine engineering, identified and managed by the Marine Product Line and Technology Resources groups of Public Works Canada, with funds provided by the Interdepartmental Panel on Energy Research and Development (PERD).

PERD was established in 1974 to coordinate research on energy by the Federal Government with objectives to provide, in conjunction with efforts in the private sector and the provinces, the technical basis for:

- maintaining oil self-sufficiency over the short term, in view of dwindling conventional supplies;

- developing a diversified energy economy, less dependant on oil and gas in the mid-term; and

- making Canadians less reliant on non-renewable energy sources in the long term.

The research work undertaken by Public Works Canada in Marine Engineering with funds from PERD has been directed particularly toward the following two main topics:

1. Ice/Structure Interaction
2. Construction and Towing of Reinforced Concrete Caissons in the Arctic.

This report is being published with a view to enhancing the technology in the field of Marine Engineering and contributing toward the objectives of PERD.

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EXECUTIVE SUMMARY

There are large uncertainties associated with ice loads on offshore structures. These uncertainties result from the random nature of the environmental parameters which influence ice loads such as ice feature frequencies, geometries, sizes, speeds of movement and mechancial properties. Uncertainties regarding ice loads are also partly a result of imperfect knowledge of the ice loading processes and parameters and uncertainties regarding the models used in calculating ice forces. These uncertainties are dealt with in probability-based design approaches adopted in offshore codes, by selecting the design load as the load associated with a certain probability of exceedance (or return period), multiplied by a load factor. The selection of design ice loads thus requires the calculation of a probability distribution of ice forces on the structure. This study has developed probabilistic models and computer programs for estimating the probability distribution of local pressures and global forces resulting from the interaction of ice with a given fixed offshore structure in any Canadian offshore location.

In order to establish the relevance of the study to the design of offshore structures, the concepts of probabilistic design as well as relevant offshore code requirements were reviewed and summarized. This review shows that the approach to defining design loads is similar in most codes. The Canadian Standards Association CSA-S471 (ninth draft) is the most detailed set of standards in describing probabilistic design criteria. Both the CSA standards and the new American Petroleum Institute API-RP2N (1987) give good information regarding ice properties and ice force calculation methods.

The model developed for calculating the probability distribution of the maximum annual global ice forces consists of the following steps:

1) Definition of ice conditions (or seasons): These include open water (summer) conditions, closed water (winter) conditions and break-up conditions.

2) Calculation of the season length: Based on data regarding season boundary dates, the probability distributions of season lengths are calculated.

3) Selection of load scenarios: Load scenarios include iceberg, ice floe and ice island collisions, first year ridge interactions and level ice movements. The driving forces from surrounding first year ice on discrete features such as multiyear floes or icebergs are considered during the winter and break-up seasons. Multiyear ridge interactions are considered as part of the interaction process of the multiyear floe in which the ridge is embedded.

4) Calculation of the level of exposure: This is done for the scenario considered during the current season. The level of exposure is defined by the frequency of occurrence for discrete loading processes such as multiyear floe interactions, or the length of time of application for a continuous loading process such as level ice movement in the active ice zones.

5) Calculation of the probability distribution of the load magnitude: This is calculated for each loading event by using a Monte Carlo simulation algorithm which generates random values from input parameter distributions and uses these values in the appropriate ice-structure interaction models to generate force values. Ice-structure interaction models used include limit momentum models for discrete areal feature collisions, local shear and crushing models for first year ridges as well as creep, bending and crushing models for level ice interactions. New ice-structure interaction algorithms were developed for areal ice features impacting the structure both in open water and winter conditions.

6) Estimation of maximum loads per load scenario: Appropriate extremal analyses are used to combine the results of 4 and 5 above into an estimate of the maximum annual load for the scenario and season under consideration. The selection of the appropriate extremal model depends on whether the random process used for the current load scenario is discrete or continuous.

7) Calculation of maximum loads for scenario combinations: The analysis is repeated and the scenario extremes are combined for different scenarios and different seasons to obtain the final annual extreme load probability distribution which can be used in selecting design loads.

The model requires the probabilistic definition of environmental input parameters such as ice concentration, velocity, thickness and mechancial properties. These parameters were analyzed in detail from publically available data and default values for all relevant parameters in the Beaufort Sea and Grand Banks areas were selected.

A model for calculating the probability distribution of the maximum annual local ice pressure on a certain panel of a fixed structure was developed. The model deals with the following aspects:

1) Exposure time: The average period of time in a year during which the design panel is loaded by a certain type of ice is calculated. This is based on estimating the probability that the combination of water depth, ice thickness and direction of ice movement are such that the panel is fully loaded by the ice.

2) Non-simultaneous peaking of the ice pressure: This is based on combination of a number of independent random processes each representing the pressure on an independent subzone of the design panel. The geometry and size of the independent zones and the pressure history on each zone are assumed to be defined from experimental data.

The probability distribution of the maximum annual pressure is then calculated on the basis of the central limit theorem and the double exponential extremal distribution.

The methodology was incorporated in a computer package for calculating global loads and local pressures for a given structure due to any of the specified loading scenario or combination of scenarios. The program considers vertical sided structures (circular and polygonal) as well as upward and downward breaking cones. The program is fully interactive and contains data checking, storage and retrieval facilities. For any input parameter, the user can use the default value or distribution (if available), or redefine the parameter distribution by using one of the standard mathematical distributions in the program library, or the data histogram itself. The analysis is then carried out and the desired load probabilistic descriptions printed in any of the common statistical formats (i.e. cumulative probability, probability density, probability of exceedance and return period).

Experimentation with the probabilistic model developed in the study leads to the following conclusions:

i) Proper characterization of the behaviour and mechanical properties of ice during large scale ice-structure interaction is essential for the evaluation of reliable design ice loads.

ii) Ice loads are not dominated by one scenario, but different scenarios may lead to high loads depending on the location and type of structure considered. There is a need to give some attention to load calculation models for scenarios that have been viewed as secondary such as first year ridge and first year level ice interactions.

iii) It is interesting to separate uncertainties due to lack of knowledge from those due to inherent randomness of a given parameter. This allows the evaluation of the value of new information regarding a certain parameter in improving design load estimates, and provides a good approach for dealing with short data records.

It is recommended that future research in these areas should include: (i) parametric studies and sensitivity analyses, (ii) investigation of the use of reliability methods to replace the time consuming Monte Carlo approach, (iii) the development of appropriate interfaces to link the present model to different environmental and ice-structure data bases, and (iv) further development of ice-structure interaction models to deal with first year rubble interaction and areal ice feature splitting.

CHAPTER 1

INTRODUCTION

This report is the result of a study carried out for the Department of Public Works under Contract No. EN-280-7-0733101, awarded to Det norske Veritas (Canada) Ltd. by Supply and Services Canada. The project was funded under the Panel on Energy Research and Development program (PERD). The study objective was to develop a probabilistic framework for estimating ice loads on fixed structures in the Canadian offshore.

1.1 Motivation

Ice is recognized as a major hazard to offshore structures in arctic and subarctic regions. As an environmental loading type, ice is dealt with in design codes on a probabilistic basis. The design load is usually based on a characteristic (or specified) load value which has a certain probability of exceedance or return period. The selection of an ice design load, therefore, requires a probabilistic description of ice forces.

Uncertainty regarding ice loads derives from the uncertainties associated with ice environmental parameters and mechanical properties which change from season to season, and are different for different locations. It is also partly due to uncertainties regarding the models used in calculating load values for a given set of conditions and parameters. Ice loads are also dependent on the type, size and geometry of the structure considered. An approach to the estimation of probabilistic ice loads should therefore be capable of considering problem specifics related to the structural geometry and site specific ice data.

In this study, a general approach for estimating probabilistic ice loads was developed. The model is general in its capability to deal with different types of ice conditions and hazards as well as different structural geometries. It uses site specific environmental data to produce ice loads for any structure with user defined geometry and size.

1.2 Overview

The goal of the present study was to develop a tool for decision-making regarding design criteria for ice loads on offshore structures. The study was therefore started by undertaking a review of the concepts of probabilistic and limit states design, and a survey of the requirements or relevant offshore codes as they relate to ice loads. The results of this review are summarized in Chapter 2.

Chapter 3 deals with the types of ice conditions and ice hazards in the Canadian offshore. Ice conditions during different seasons of the year determine the type and speed of interactions in different ice zones. Also the types of hazards present in different locations dictate the possible loading scenarios. A summary of the ice regime and ice types in different Canadian offshore locations is given. Ice parameters needed for ice load calculations, such as feature sizes and geometries, ice thickness, speed of movement, ice concentrations and ice mechanical properties were also analyzed for the purpose of creating a default data base of environmental parameters. This concentrated on the Beaufort Sea and the Grand Banks areas where different data sources were reviewed and analyzed statistically to find representative distributions for different input parameters. The results of this analysis are also described in Chapter 3.

Ice-structure interaction algorithms were selected based on the state of the art in ice load computation methods and new models were developed where needed. New models for dealing with eccentric impacts in open water and concentric impacts in closed water conditions were developed. In developing these models, attention was given both to realistic representation of the ice load scenario and to simplicity. Local ice behaviour was based on the structural geometry and the speed of the impact. The different ice failure and behaviour modes, and the models used for each type of interaction are summarized in Chapter 4.

Chapter 5 describes the probabilistic approaches developed and used in the final model. This includes the selection of stochastic processes to represent each load scenario, and the extremal models to be used in calculating the maximum load for each process type. Parameters needed to characterize these processes are the level of exposure and severity of the load for each scenario. Models for estimating the exposure level and load intensity from the environmental and mechanical ice parameters are given for each loading scenario. This chapter also includes the description of a newly developed model for estimating the maximum local pressure probability distribution for a given area of the structure. The model takes into account the probability of the given area being loaded by ice and the non-simultaneous failure of ice in different zones of the contact area. Finally, a model for dealing with short data records and uncertainties due to lack of knowledge is presented.

The development of the overall model and computer program are described in Chapter 6, and the results of sample problems are given. A detailed description of the software is given in Volume II of this report.

CHAPTER 2

REVIEW OF PROBABILISTIC DESIGN APPROACH AND RELEVANT CODE REQUIREMENTS

2.1 General

The need for probabilistic approaches to deal with ice loads results from the uncertain nature of these loads. Uncertainties in structural design problems are dealt with by using probabilistic design methods in which the safety of a structure is measured by its reliability (defined as the probability of survival). Codes of practice have been developing simple approaches which are calibrated such that a certain target reliability is, on average, met.

In order to establish the relevance of the probabilistic ice load approach to structural design, reviews of probabilistic design concepts and the requirements of different offshore codes of practice have been carried out for the study. The results of these reviews, presented in this chapter, define the overall design philosophy and the practical context in which the study results are to be used.

2.2 Concepts of Probabilistic Design

2.2.1. Structural Reliability:

The reliability of a structure or component is defined as its probability of survival, p_s, which is related to the probability of failure, p_f by:

$$p_s = 1 - p_f \tag{2.1}$$

Considering the uncertainties associated with load effects and structural resistance, the probability of failure (or reliability) provides a meaningful measure of the adequacy of a structure or member. Failure is defined in relation to different possible failure modes, commonly referred to as limit states. For example, ultimate (or collapse) limit states represent the inability of the structure to resist the imposed load effects and can be associated with large inelastic displacements and, for offshore structures, capsizing or sinking. On the other hand serviceability limit states are defined as the inability of the structure to meet its normal use or durability requirements (NPD, 1987). Examples are excessive deformations that affect the usability of machinery and equipment.

The performance of a structure in relation to a certain limit state, can be described as a function of a set of basic parameters (X_i, $i = ...,n$). For example, the deformation of a structural element, Δ can be expressed as a function of the load effects, material properties and geometric parameters:

$$\Delta = \Delta(X_1, X_2, \dots X_n) \tag{2.2}$$

Assuming that the maximum allowable deformation for a certain serviceability condition is Δ_0. The boundary between failure and survival can, in this case, be described by $\Delta = \Delta_0$ or:

$$\Delta - \Delta_0 = 0 \tag{2.3}$$

Failure occurs if $\Delta - \Delta_0 > 0$ while the structure is safe for $\Delta - \Delta_0 < 0$. Substituting Eq. 2.1 into 2.3 one can write:

$$g(X_1, X_2, \dots X_n) = 0 \tag{2.4}$$

in which Δ_0 was incorporated in the function g, such that failure occurs if $g > 0$ and no failure occurs if $g < 0$. The function g is called the limit state function, and it separates the failure region ($g > 0$) and the safe region ($g < 0$).

This concept is further illustrated in Fig. 2.1, where the problem is simplified by assuming that the limit state function depends only on two basic parameters, $g(X_1, X_2)$. This simplification is convenient because it allows the visual representation in Fig. 2.1, but the concept is equally applicable to an n-dimensional space. The limit state function can then be plotted in the (X_1, X_2) plane, and the failure and safe regions are as depicted in Fig. 2.1. If one envisages a perpendicular axis to the (X_1, X_2) plane on which a joint probability density function is defined, the probability of

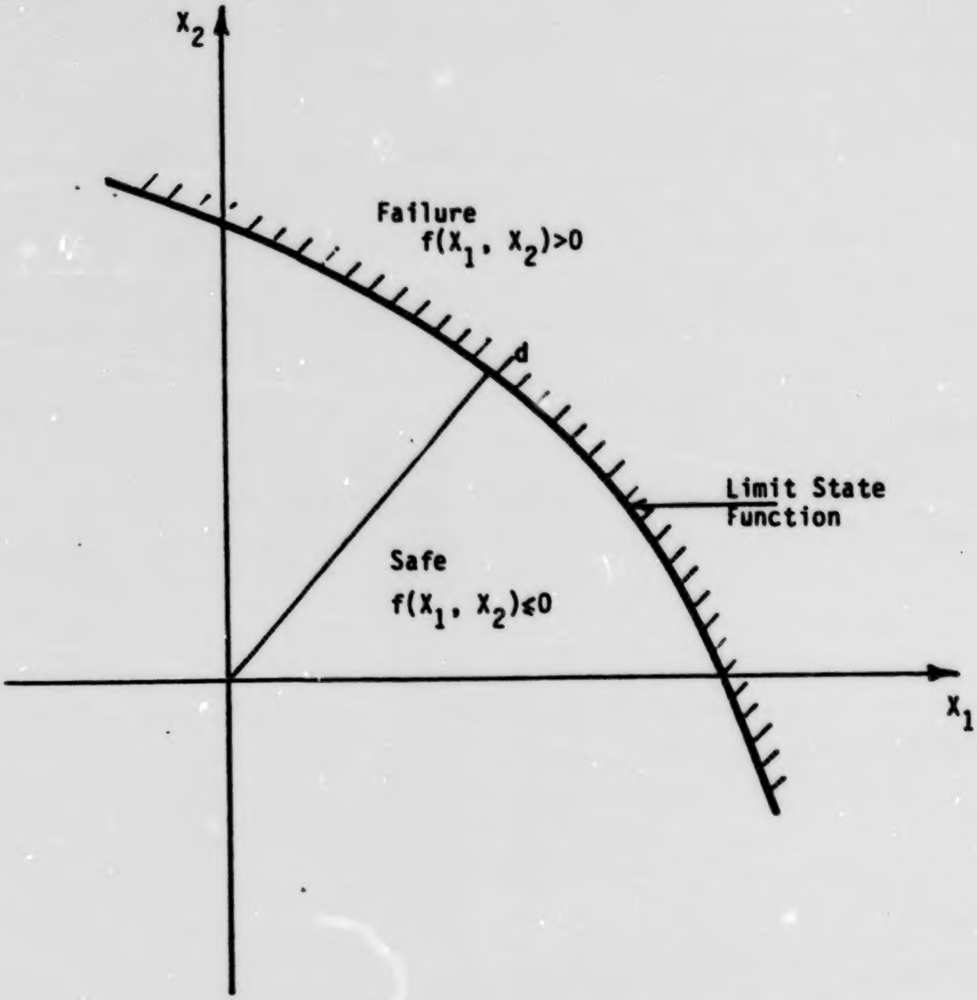

X_2
Failure
$f(X_1, X_2)>0$
d
Limit State Function
Safe
$f(X_1, X_2)\leqslant 0$
X_1

Fig. 2.1 Illustration of a Reliability Problem in Two-Dimensional Space

failure is represented by the volume under the density function and over the failure region. The calculation of the failure probability in the general n-dimensional case is a complex task. Much research has been devoted to this problem, and solutions with different levels of detail and accuracy are available (see Thoft-Christensen and Baker, 1982 or Madsen et al, 1986).

The above discussion concentrates on the reliability of a single component. Methods are available to obtain reliability estimates (or bounds) for systems composed of several components.

2.2.2 Design Load and Design Resistance

Consider a case where the resistance of a component in a certain limit state can be described by a single parameter R, and the corresponding load effect by the single parameter S. Failure occurs if S exceeds R, thus the limit state function is given by:

$$g\,(S, R) = S - R \tag{2.5}$$

In Fig. 2.1 this would be represented by a straight line through the origin with a slope of 45°. The probability of failure can then be calculated as:

$$P_f = \int_{all\ s} \int_{r\,<\,s} f_{R,S}\,(r\,,s)\ ds\ dr \tag{2.6}$$

Assuming that R and S are independent $f_{R,S}$ (r,s) can be replaced by $f_R(r) \cdot f_S(s)$, and Eq. 2.6 simplifies to:

$$P_f = \int_{all\ s} f_S(s)\ \Big(\int_{r<s} f_R(r)\ dr\Big)\ ds \tag{2.7}$$

i.e.

$$P_f = \int_{all\ s} f_S(s)\ F_R(s)\ ds \tag{2.8}$$

which is a convolution integral.

The formulation in this section can be graphically represented as in Fig. 2.2. The load and resistance distributions can be plotted on the same axis by virtue of the assumption of independence (i.e. there is no need to consider the bivariate distribution). The possibility of failure exists because of the overlap between $f_R(r)$ and $f_S(s)$, and the probability of failure can be reduced by reducing the overlap. (Note that the probability of failure as given by Fig. 2.2 is not equal to the overlap area).

The overlap between $f_R(r)$ and $f_S(s)$ depends on the parameters of the two distributions. It can be seen that one can reduce this overlap, and consequently p_f, by moving the distributions further apart through adjusting their mean values (increasing the resistance mean and/or reducing the load mean). p_f can also be reduced by reducing the spread (i.e. variance) of either or both distributions.

There are several approaches that can be adopted to select design criteria based on the above concepts. The most general is to use a measure of the utility associated with each design alternative which takes into account the probability and consequences of failure, and the costs of the system. This can then be compared for different possible alternatives and the design can be selected on the basis of optimizing the utility or objective function. This basic approach is justified for new problems where experience is lacking and for systems which involve large investments. For most practical design problems, however, a simpler approach is needed. This is usually achieved by developing codes of practice which give the design engineer fixed values of the load and resistance which can be used in deterministic design. These values referred to as the design load and design resistance, are selected and calibrated such that the resulting structure or structural member has, on average, a certain target reliability. This target reliability can be selected to optimize the economic and social consequences associated with the structure or member. The application of this procedure in structural codes is discussed in detail in the literature (e.g. CIRIA, 1977).

2.2.3 Characterization of Design Loads:

In practice the target reliability can be achieved by choosing a design load on the right hand side tail of the load distribution and a design resistance on the left hand side tail of the resistance distribution such that the probability of occurrence of R and

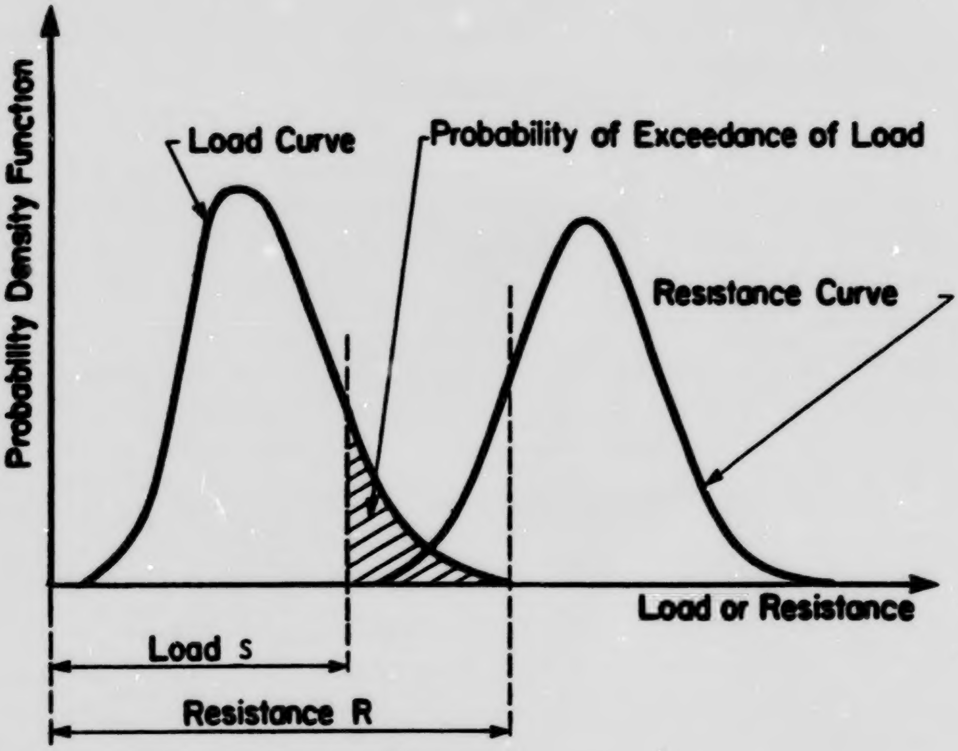

Probability Density Function
Load Curve
Probability of Exceedance of Load
Resistance Curve
Load or Resistance
Load S
Resistance R

Fig. 2.2 Illustration of the Calculation of the Probability of failure for Independent Load and Resistance

S combinations with R < S is sufficiently small (see Fig. 2.2). The design load value S_d is usually defined by multiplying a certain specified (or characteristic) load value S_s by a partial factor γ_S. Partial factors for loads are usually > 1. The choice of the specified load value depends on the type of loading and the shape of the distribution. For permanent loads with well defined distribution types and well known variances, the average or expected value is usually used. On the other hand, for environmental loads with large variability in time, such as ice loads, it is more appropriate to select a specified value on the tail of the maximum load distribution. This eliminates the effects of some of the uncertainties associated with the distribution shape. In either case, the partial load factor is calibrated such that when used with the specified load value and the appropriate design resistance it will result on average in the target reliability value.

The choice of a specified load value on the distribution tail can be based on different probabilistic measures, the most common of which are as follows:

i) The probability of exceedence E calculated as:

$$E_S(s) = 1 - F_S(s) \tag{2.9}$$

ii) The return period T defined as the average number of trials (or observations) until a certain value on the distribution is exceeded once. It can be shown that if the load distributions for the different trials are assumed to be independent and identically distributed, then T is given by (Gumble, 1958):

$$T_S(s) = \frac{1}{1-F_S(s)} > 1 \tag{2.10}$$

For time related loading processes, $T_S(s)$ is given in units of time equal to the period represented by $F_S(s)$ (i.e. if $F_S(s)$ is the maximum annual load, then $T_S(s)$ is given in years).

The appropriateness of using either of the above probabilistic measures depends on the length of data record. It is noted that equivalence between the two measures is dependent on the validity of the assumption of different trials being independent and the load value in all trials being identically distributed.

2.3 Relevant Code Requirements and Recommended Practice

As discussed in Section 2.1, the calculation of the design ice load requires a probabilistic description of the maximum load associated with ice-structure interaction events. Models and procedures for developing this probabilistic description will be discussed in detail in the following chapters. At this point, however, it is necessary to mention that the development of the extreme ice load probability distribution requires the use of probabilistic descriptions of the relevant environmental parameters and ice mechanical properties in deterministic ice-structure interaction algorithms and appropriate probabilistic and extremal models (see Fig. 2.3). Current codes and standards have addressed several aspects of this methodology. These include probabilistic definitions of the design criteria, as well as ice mechanical properties, ice-structure interaction modelling and parameters influencing ice loads. Some ship rules were also reviewed in order to obtain relevant information on local pressures. Each of the standards reviewed is summarized in a separate section in the following.

2.3.1 The Canadian Standards Association CSA-S471 (ninth draft, 1988).

a) General

The CSA Code for the design, construction and installation of fixed offshore production structures gives information both on the probabilistic selection of design criteria and methods for estimating ice loads. The code is based on limit states design using partial factors but more general probabilistic design methods are allowed provided the same safety levels can be demonstrated. Limited states are classified into ultimate limit states and serviceability limit states (Sec. 4.6).

The CSA S471 also allows for two safety classes. Class 1 where failure poses a high risk to human or environmental safety and class 2 for which the risk to human and environmental safety due to failure is low. It is noted that these safety classes can be

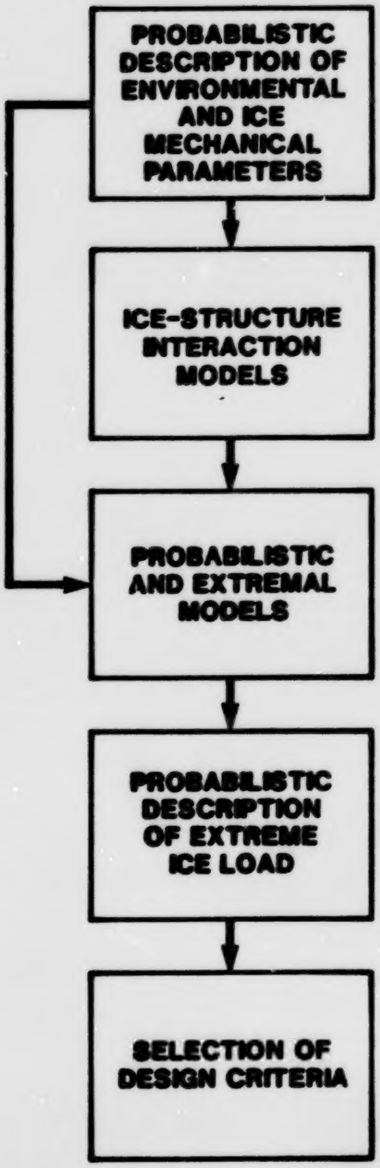

PROBABILISTIC DESCRIPTION OF ENVIRONMENTAL AND ICE MECHANICAL PARAMETERS
ICE-STRUCTURE INTERACTION MODELS
PROBABILISTIC AND EXTREMAL MODELS
PROBABILISTIC DESCRIPTION OF EXTREME ICE LOAD
SELECTION OF DESIGN CRITERIA

Fig. 2.3 Overall Methodology for Selection of Design Criteria

applied to the whole structure or to different elements within the structure (Sec. 4.5.2, Appendix A).

Environmental loading processes (including ice) are divided into frequent and rare. Frequent environmental loads are associated with frequent environmental processes which include continuous processes and discrete processes with an annual probability of occurrence greater than 0.5. Rare environmental loads, on the other hand, are associated with rare environmental processes which are defined as discrete processes with an annual probability of occurrence less than 0.5 (Sec. 3.1).

b) Design Ice Loads

The design load is defined as the specified load multiplied by the load factor. As an environmental load, ice is to be considered in appropriate combination with other loading types (Sec. 6.2.5.6, Tables 6.1 and 6.2). The annual probability of exceedance for the specified load and load factors in the CSA-S471 code are summarized in Table 2.1. There is also a provision specifying that rare events with annual probability of occurrence less than 10^{-4} need not be considered in the design.

Table 2.1
Annual Probability of Exceedance and Load Factors in the CSA-S471 Code

	Safety Class 1		Safety Class 2	
	Annual Probability of Exceedence	Load Factor	Annual Probability of Exceedence	Load Factor
Frequent Event	10^{-2}	1.35	10^{-2}	0.9
Rare Event	10^{-4}	1.0	10^{-2}	1.0

c) Ice Load Calculation

Relevant information for calculating ice loads is given in Sec. 5.4 of the CSA standards. This section specifies some of the parameters that need to be considered for this purpose. These include the probability of occurrence of various ice types and their geometric characteristics in the different ice zones (Sec. 5.4.2), ice movement rates (Sec. 5.4.3) and mechanical properties. Sources of environmental information are listed in Appendix B of the standards. Appendix E of these standards is devoted to a treatment of ice mechanics and load calculation approaches.

2.3.2 The American Petroleum Institute Revised API-RP2N (draft, 1987)

a) General

This recommended practice for offshore structures in ice environments concentrates on load calculation methods and the necessary parameters and does not give explicit criteria for the selection of design loads. It provides for the distinction between extreme environmental conditions which have return periods of several times the design life, and normal environmental conditions which occur frequently (Sec. 3.2).

b) Design Considerations

The API-RP2N recognizes that large (and presumably rare) ice features represent an exceptional class of loading. This class may be dealt with by accepting a risk of damage to the structure without loss of life or harm to the environment (Sec. 2.3). This can be done by ice surveillance, active defense and shutdown and abandonment procedures.

c) Ice Load Calculation

The determination of ice loads is dealt with in detail in this recommended practice. Sec. 3.5 (ice considerations) gives an account of the physical, mechanical, and morphological properties of ice, as well as a description of ice movement rates and geometries. References which describe these properties are given and guideline values for some of the parameters are included.

Sec. 4.4 deals with the determination of ice loads. In Sec. 4.4.1, a comprehensive list of the parameters influencing ice load magnitudes is given. These are:

- the geometry of the ice feature
- the physical and mechanical properties of the ice feature
- the failure mode induced in the feature or in the surrounding ice sheet as a function of the structure geometry
- the degree and eccentricity of contact between the ice feature and the structure
- the velocity of the ice feature
- the environmental forces available to drive the ice feature
- the inertial effects in both the ice and the structure
- friction between the structure and ice
- compliance of the structure
- non-simultaneous failure of the ice in a given mode
- simultaneous occurrence of different failure modes

The calculation methods given consider load calculations limited by ice strength, as well as those limited by driving forces and ice feature momentum. Of special interest to the subject of this report is the mention of probabilistic methods for ice load estimation (Sec. 4.4.7) and the phenonenon of non-simultaneous failures (Sec. 4.4.8).

2.3.3 Det norske Vertias Rules (1977)

a) General

DnV's Rules for the design construction and inspection of offshore structures allow for the use of probabilistic design and working stress design, but are based on a limit states design format by use of partial factors (referred to as load coefficients in these rules) (Sec. 4.2, 4.3 and 4.4). The design load is obtained by multiplying the load coefficient by a characteristic load value (note the difference in terminology from the CSA standards where the term specified load was used).

The rules consider four types of limit states namely ultimate limit states, fatigue limit states, progressive collapse limit states, and serviceability limit states (Sec. 4.4.4). Different design phases are considered covering the construction, transportation, installation, operation and retrieval conditions (Sec. 1.1).

b) Ice Design Loads

These can be obtained from sections dealing with environmental loads. The characteristic load value is defined as the most probable largest value in a time period equal to the design period (an analogous definition based on the lowest value is given for cases where a reduction in the load results in reduced safety). The design period is to be normally taken as 100 years for operating conditions (Sec. 5.2.4). For all other phases (see (a) above) the design period is to be taken equal to 3 times the duration of the relevant phase (Sec. 5.2.4.3). For operations or short term phases, reliable forecasting may be used in calculating the characteristic load.

The load coefficients for ice loads in ultimate limit states are 0.7 for ordinary loading and 1.3 for extreme loading (Sec. 4.4.4). For all other limit states the load coefficient is equal to 1.0.

c) Ice Load Calculation

It is specified that ice loads are to be calculated from environmental conditions including ice concentration, type, mechanical properties, velocity, thickness and probability of encounter (Sec. 3.5.4). Loads are to be calculated from full scale or model tests, or recognized theoretical models (Sec. 5.3.5).

2.3.4 Norwegian Petroleum Directorate (1987)

a) General

The Norwegian Petroleum Directorate's acts, regulations and provisions for the petroleum activity recommend the use of a partial factor format for well known loading types and a probabilistic approach for highly uncertain loads (Sec. 2.4.3). The definition of the design load, characteristic load and load coefficient, as well as the brief account of ice load calculation methods are similar to those in DnV rules.

b) Ice Design Loads

Load effects with annual probability of occurrence of less than 10^{-4} can be disregarded in the analysis. Relevant characteristic load and load coefficient values for normal operation are as follows:

- For serviceability, fatigue and progressive collapse limit states the load coefficient is 1.0 (Sec. 4.2.2 and 4.2.3). The characteristic load for progressive collapse limit state corresponds to an annual probability of exceedence of 10^{-4} for the purpose of demonstrating that only local damage occurs where abnormal effects occur, and to an annual probability of exceedence of 10^{-2} for the purpose of demonstrating that the damaged structure will resist progressive total collapse under the defined environmental conditions (Sec. 4.3).

- For ultimate limit states the characteristic load value corresponds to an annual probability of exceedence of 10^{-2}. The load coefficient is 0.7 or 1.3 depending on the load combination (Sec. 4.2.4).

2.3.5 Federation Internationale de la Precontrainte (1985)

The FIP recommendations for the design and construction of concrete sea structures uses the same design phases as defined by DnV rules (Sec. 1.2). Three safety classes are defined with Class 1, 2 and 3 representing structures for which the consequences of failure include very little, limited and great risk to human lives and environmental safety (Sec. 4.3). As in the CSA Standards only ultimate and serviceability limit states are defined, with the ultimate limit states including fatigue and progressive collapse (Sec. 4.4.2). The characteristic load is defined as in DnV rules and 100 year return period is specified for extreme environmental loads. For normal conditions shorter return periods (e.g. one month) can be considered (Sec. 4.6). The load factors should be chosen to account for (Sec. 4.5):

- unusual load deviations
- inaccurate assessment of loading effects
- variations in dimensions during construction
- importance of the limit state being considered
- safety class
- reduced probability of simultaneous occurrence of load combinations.

For ice load calculation methods the FIP standards refer to the API-RP2N recommended practice (Sec. 2.3.5).

2.3.6 British Standards BSG235 (1982)

The British Standard Institution Code of Practice for Fixed Offshore Structures does not give consideration to sea ice and iceberg loading since these environmental conditions were deemed irrelevant for the geographic area addressed in the code (Sec. 2.11). As in other codes, environmental conditions are separated into normal and extremal. These standards are different from others in selecting the extreme design environmental conditions to correspond to 50 years return period or an annual probability of exceedance of .02, for structures having an intended service life of equal to or less than 30 years. These probabilistic load levels can be adjusted for structures having a service life significantly shorter or significantly longer than 30 years.

2.3.7 Det norske Veritas Rule Proposal RP-SD-50 (1985)

The DnV rule proposal for steel ships, Part 5 Chapter 1, "Ships for Navigation in Ice", was reviewed for relevant information on local ice pressures. The design ice pressure, p is to be taken as:

$$p = F_b \, p_0 \quad \text{MPa} \tag{2.11}$$

where F_b is a correction factor for the size of the contact area A_c (m^2):

$$F_b = \sqrt{\frac{1}{A_c + 1}} \tag{2.12}$$

and p_0 is the basic pressure in kN/m^2. p_0 is given by:

$$p_0 = F_a \, \sigma_{ice} \tag{2.13}$$

Where F_a is a correction factor for the area of the ship being considered F_a is 1.0 for bow area which appears to be most similar to fixed structure conditions. σ_{ice} is the nominal ice strength in MPa which varies with the ice thickness and conditions. Values of σ_{ice} are given in Table 2.2.

Other information regarding ice pressures obtained from tests that better represent fixed structures is available in the literature. This information along with suggested statistical approaches for the selection of design local ice pressures for fixed structures will be given in Sec. 5.5.

Table 2.2

Nonimal Ice Pressures (Ice Breakers)

Ice Type	Ice Thickness (m)	Nominal Ice Strength (MPa)
Winter Ice with Pressure Ridges	0.5	4.2
	1.0	5.6
	1.5	7.0
Winter ice with pressure ridges and multi-year floe and ice inclusions	1.0	7.0
	2.0	8.5
	3.0	10.0

CHAPTER 3

ICE HAZARDS AND STATISTICAL ANALYSIS OF ICE DATA IN THE CANADIAN OFFSHORE

3.1 General

The Canadian Offshore can be divided into six regions with distinct ice regimes. These are as follows:

i) The Beaufort Sea
ii) The High Arctic
iii) Baffin Bay and Davis Strait
iv) Hudson Bay
v) Labrador Shelf
vi) Grand Banks

The purpose of the discussion in this chapter is to give a brief account of the ice regimes in each of these areas, identify hazardous ice features, characterize year-round ice conditions and define ice loading scenarios accordingly. This chapter also includes the results of detailed statistical analysis of data regarding the ice parameters needed to determine the load resulting from each scenario. The data analysis of ice parameters concentrated on the Beaufort Sea and the Grand Banks since these are the two areas where bottom founded structures have been under consideration, resulting in the development of good data bases. The purpose of this data analysis was to develop appropriate probability distributions for the input parameters to the probabilistic ice force model. The Beaufort Sea results were obtained from DnV's previous work, whereas the Grand Banks parameters and data were analyzed in detail under the present study. The resulting distributions were used in the computer model as default values which can be modified by the user if more or better quality data are available.

3.2 Types of Hazardous Ice

3.2.1 Level First Year Ice Sheet

First-year ice forms by the freezing of sea water in the winter season and usually melts in the summer. First year ice is saline and grows in thickness throughout the winter at rates depending on the air temperature.

3.2.2 Deformed First Year Ice Features

These form in dynamic ice areas where environmental forces act on the ice cover causing ice to fail along weak zones and deform into one of the following features:

a) Rafted Ice which forms if one sheet rides over the other until friction between the sheets reaches the driving force or the buckling load in the sheet. These thickened features often represent the thickest ice in areas of thin ice cover.

b) First Year Ridges which result from continued pressure of the ice at the failure plane. The pile of rubble formed from this process acts as a trigger mechanism to fail thicker ice sheets later in the season forming the ridge. As the freeze up continues, the rubble pieces freeze together and the ridge becomes more consolidated. First year ridges may exceed 30m in thickness.

3.2.3 Multi-Year Floes and Hummock Fields

If first year ice survives the summer season, much of its salt content is lost during the partial melt. During the next freezing season, water freezes in the voids which were originally filled with salt and impurities and the resulting ice becomes stronger. Details of this process are described in Pounder (1965). As this process is repeated year after year, stronger, thicker ice, which is referred to as multi-year ice, is formed. Multi-year floes mostly drift from the Polar pack under the action of southwesterly winds.

Multi-year floes can contain large pressure ridges which, unlike first year ridges, are consolidated and refrozen into solid ice masses. Heavily deformed multi-year floes are referred to as hummock fields. Multi-year floes can be several kilometers across.

3.2.4 Icebergs

Most icebergs originate from the glaciers of east and west Greenland. Glacial ice is formed from snow, which is compressed under its own weight into ice. Icebergs from West Greenland accumulate in Baffin Bay before the Labrador current carries them south across the Labrador Shelf and into the Grand Banks. Of about 40,000 calved each year, an average of 400 survive melting to reach the 48° parallel. When they initially calve from the glaciers, icebergs can weigh several million tonnes, but by the time they reach the Grand Banks most weigh less than 200,000 tonnes. Due to their large drafts, icebergs are principally driven by currents. Small icebergs (referred to as bergy bits) may be accelerated by the particle motion of waves thus reaching speeds several times their drift speeds.

3.2.5 Ice Islands and Ice Island Fragments

These are also composed of glacial ice which breaks off from the face of the Ward Hunt ice shelf on the north coast of Ellesmere Island. Most drift in a south-west direction along the edge of the archipelago following the general clockwise drift of the Polar Pack. Occasionally ice islands break away from the pack and drift across the Beaufort Sea under the influence of wind, currents and local ice cover. The mean diameter of ice islands is 12 km and the average thickness is 40m (Dunwoody, 1983).

Ice islands can be grounded and break up into several pieces resulting in a population of ice island fragments which average about 70m in diameter (Spedding, 1974).

3.3 Ice Zones

Ice is usually divided according to its freedom of motion into two zones:

a) Landfast ice zone which is also referred to as the fast ice zone, and represents ice that is mostly grounded and attached to the shore line. In the Canadian Beaufort Sea for example, this zone usually extends from the shore line to a water depth of approximately 20m (EIS, 1982). The ice in this zone exhibits very little movement during the winter season.

b) Pack ice zone is any ice zone beyond the landfast ice. Typically, pack ice is constantly moving under the effect of the environmental driving forces.

3.4 Ice Regimes

The term ice regime is used to describe the annual cycle of ice cover formation and decay in a given area (Markham, 1981). This is important information for ice-structure interaction because it defines the level of exposure of the structure to different ice environmental conditions. Two events are of significance in describing the ice regime namely, freeze-up and break-up. The ice regimes of the different Canadian Offshore regions are summarized in Table 3.1. The maximum ice thickness given in Table 3.1 represents the thickness of the first year level ice at the end of the winter season. Thicker ice inclusions such as first year ridges, multi year floes, ice islands or icebergs may exist in the ice. Break-up and freeze-up dates are approximate averages for each area and are intended only as a general indication of the ice regime. The actual break-up and freeze-up dates can vary substantially from location to location within the same geographic region. The information in Table 3.1 is obtained from Markham (1981), Lindsay (1977), Appleby (1983) and Marcellus et al (1987).

3.5 Ice Conditions and Loading Scenarios

Three distinct classes of ice conditions were considered in the study:

a) Open water conditions: These represent summer seasons characterized by free movement of individual ice features without obstruction from the annual first year ice cover.

Table 3.1

Ice Regimes in Different Canadian Offshore Regions

No.	Region	Freeze-Up Date	Break-Up Date	Maximum First Year Ice Thickness (m)
1	Beaufort Sea	late October	late June	2
2	High Arctic	late September	late July	2
3	Baffin Bay and Davis Strait	late October	late July	2
4	Hudson Bay	late October	late May	1.5 - 2
5	Labrador Shelf	late November	April/May	1 - 1.5
6	Grand Banks	N/A	N/A	1.0

b) Full ice cover conditions: These represent winter conditions where first year ice grows inbetween any multi year or glacial ice features, resulting in close to 100% ice cover. Ice movements during full cover conditions can be expected to be much slower than the movement of individual features in open water. On the other hand, ice features such as multi year floes can be pushed against structures by the surrounding level ice.

c) Partial Ice Cover Conditons: These represent the break-up period where the sea is not completely frozen but the total ice concentration is too high to represent open water conditions. Intermediate ice movement speeds between those for full ice cover and open water conditions can be expected. Forces from discrete features (e.g. multi-year floes or icebergs) will be influenced by the partial confinement caused by the partial ice cover.

The choice of an ice structure interaction model for the estimation of the interaction force is dependent upon two factors, the global interaction scenario and the local ice deformation mode. The term global interaction scenario is used to represent the environmental conditions and ice feature type. Different possible scenarios in the pack ice zone of different Canadian offshore regions, are listed in Table 3.2. The scenarios in Table 3.2 apply to the open water and partial ice cover conditions in both the landfast and pack (active) ice zones. For the landfast zone in full ice cover conditions, the movement rates are very small and consequently the probability of interaction between the structure and any discrete feature in the ice (such as first year ridge or multi-year floe) is negligible. Therefore, the only scenario applicable in the landfast zone in full ice cover season is the level ice movement.

For the purpose of selecting a global model for ice structure interaction, the combinations given in Table 3.2 can be grouped into 4 basic scenarios. These are as follows (see Fig. 3.1):

1. Interaction with a level ice sheet
2. Interaction with a first year ridge
3. Interaction with a free floating areal ice feature, including first year floe, multi-year floe, iceberg, ice island or ice island fragment
4. Interaction with an areal ice feature (as in 3. above) which is surrounded by first year ice cover.

The basic scenarios representing each ice condition/ice type combination are given in the last column of Table 3.2.

The ice parameters needed for force calculation in each of the above 4 scenarios are listed in Table 3.3. These parameters are self explanatory except for the following:

- Break-off event: This is an event where a large area of the landfast ice breaks off (usually during a storm) and starts moving at speeds higher than those typical of landfast ice movement.

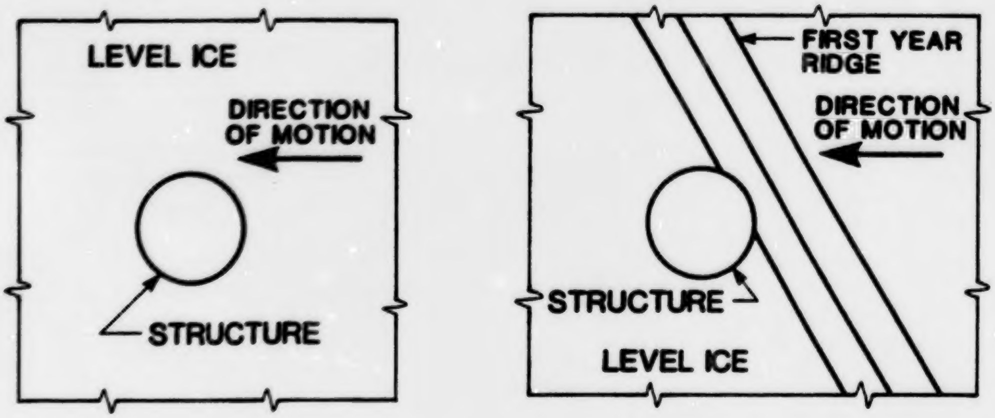
- Peak movement speed: Landfast ice movement is characterized by distinct high peaks. The process is therefore quantified at those peaks during which the maximum ice forces can be expected to occur.

Table 3.2

Possible Load Scenario In Pack Ice Zones

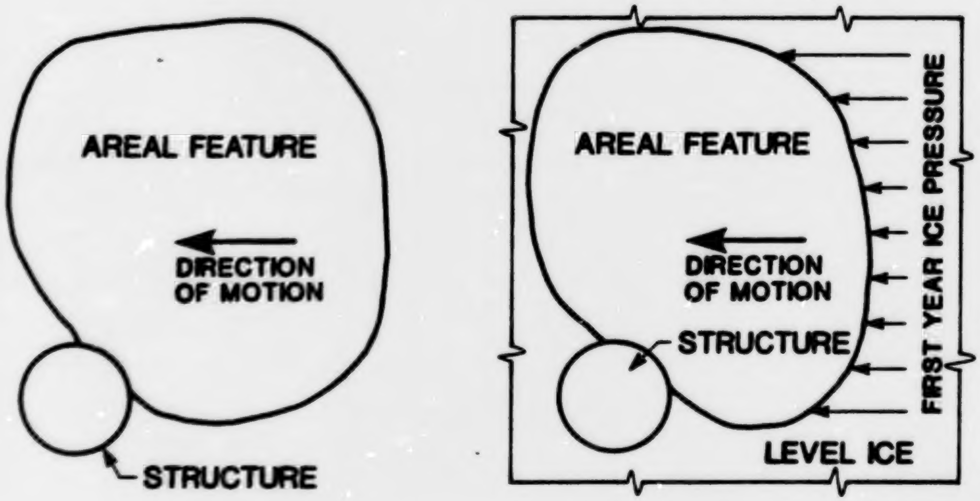
Ice Conditions	Ice Type	Beaufort Sea	High Arctic	Baffin & Davis	Hudson Bay	Labrador Shelf	Grand Banks	Interactio Scenario Number
Open Water	FY floe	X	X	X	-	X	X	3
	MY floe*	X	X	X	-	X	-	3
	Iceberg	-	X	X	-	X	X	3
	Ice island	X	X	X	-	X	-	3
	Ice island Fragment	X	X	X	-	X	-	3
Full Ice Cover	FY level ice	X	X	X	X	X	N/A	1
	FY ridge	X	X	X	X	X	N/A	2
	MY floe*	X	X	X	-	X	N/A	4
	Iceberg	-	X	X	-	X	N/A	4
	Ice island	X	X	X	-	X	N/A	4
	Ice island Fragment	X	X	X	-	X	N/A	4
Partial Ice Cover	FY level ice	X	X	X	X	X	X	1
	FY ridge	X	X	X	X	X	-	2
	MY floe*	X	X	X	-	X	-	4
	Iceberg	-	X	X	-	X	X	4
	Ice island	X	X	X	-	X	-	4
	Ice island Fragment	X	X	X	-	X	-	4

* including MY ridges or hummock fields


LEVEL ICE
DIRECTION OF MOTION
STRUCTURE
FIRST YEAR RIDGE
DIRECTION OF MOTION
STRUCTURE
LEVEL ICE

1. Level Ice

2. First Year Ridge


AREAL FEATURE
DIRECTION OF MOTION
STRUCTURE
AREAL FEATURE
DIRECTION OF MOTION
STRUCTURE
FIRST YEAR ICE PRESSURE
LEVEL ICE

3. Free Floating Areal Feature

4. Areal Feature in First Year Ice

Fig. 3.1 Illustration of the Basic Global Ice Load Scenarios

Table 3.3

Ice Parameters Required for Each Load Scenario

No.	Scenarios	Ice Zone	Parameters
1	Level Ice	Landfast	- Frequency of movement events including the frequency and duration of a break-off event - Average duration of break-off events - Ice thickness - Peak movement speed - Frequency of speed peaks - Creep law constants - Average ice pressure component
		Pack	- Ice thickness - Creep law constants - Extremal ice pressure component - Average ice flexural resistance - Extremal ice flexural component - Ice elastic modulus - Ice poisson's ratio - Creep-crushing transition
2	First Year Ridge	All Zones	- FY ridge concentration - FY ridge length - Ice velocity - FY ridge height - FY ridge cross section geometry - Rubble cohesion - Rubble friction angle
3	Free Floating Areal Feature	All Zones	- Ice density - Feature velocity - Feature size - Feature thickness - Feature shape and geometry - Ridge height (if present) - Ridge orientation (if present) - Ridge length (if present) - Ridge geometry (if present) - Eccentricity - Added mass - Ice pressure - Ice flexural resistance - Ice elastic modulus - Ice poisson's ratio
4	Areal Feature in First Year Ice	All Zones	- All parameters in 3 above - FY ice thickness - FY ice pressure

- Extremal ice pressure and flexure component: This defines the randomly changing component of the ice pressure or flexural stress around its mean value. The extreme of this value is defined as the maximum value within a fixed time interval.

All parameters must be defined in their complete ranges. Data with cut-off values (e.g. ridges with smaller heights than .75m are usually not measured) must be adjusted to calculate the full distribution from the truncated data before using it in the model.

3.6 Statistical Characterization of Ice Parameters

3.6.1 Approach

Uncertainty regarding the maximum ice load resulting from a given load scenario is partly a result of uncertainties regarding the ice parameters during each occurrence of the scenario. These parameters must therefore be described probabilistically using the appropriate statistical ice data for the location of interest. The chi-square goodness of fit test can be used for this purpose. This test compares the data histogram to an assumed analytical probability density function (e.g. gamma, normal or lognormal). The deviation of the data from the distribution is quantified by the chi-square statistic (χ^2), which is given by:

$$\chi^2 = \sum_{i=1}^{k} \frac{(0_i - E_i)^2}{E_i}, \tag{3.1}$$

where 0_i is the observed number of points in bin i (from data);

E_i is the estimated number of points in bin i (from distribution); and

k is the number of bins.

It can be shown that the deviation χ^2 itself (given by Eq. (3.1)) has a Chi-square probability distribution which depends on the number of bins k, hence the name of the test. The level of significance is defined as the probability that the calculated deviation χ^2 is to be exceeded. A level of significance of .05, for example, means that one is willing to accept the hypothesized distribution as a good model for the data if the resulting deviation is less than the deviation associated with a probability of exceedance of .05($\chi^2_{.05}$). Details of this statistical test can be found in Benjamin and Cornell (1970) and Cochran (1952).

The purpose of the analysis reported in this section was to select representative probability distributions for the different ice parameters required for the probabilistic ice model for the Beaufort Sea and the Grand Banks regions. These distributions are used as default values in the final computer program. The above two regions were concentrated on because bottom founded structures have been considered in those areas. The model is, however, applicable to all other regions listed in Sec. 3.1 provided that the appropriate data is entered. It is noted that parameter values can vary significantly within each geographic region and that the values given should be checked and modified using location specific data for each application.

For each set of data, possible representative density functions were selected. These were then listed using DnV's software CHIFIT (Nessim, 1987) and a distribution was selected based on the results of the test (the distribution with the highest level of significance). An example of this analysis is given in Figure 3.2 and Table 3.4 for the thickness of multi-year floes in the summer. The selected distribution in this case is a gamma function with a mean of 3.9m and standard deviation of 1.58m. For cases were no suitable fit was found, an option for entering the data histogram itself in numerical format is included in the model. The distribution type in this case is referred to as numerical. Default values of parameters for which no data was found were based on judgement. These values are summarized in Sections 3.6.2 and 3.6.3.

3.6.2 Parameter Distributions For the Beaufort Sea

The selected Beaufort Sea parameter distributions are given in Tables 3.5 to 3.10. More detailed information on the derivation of these distributions can be found in Nessim et al (1986).

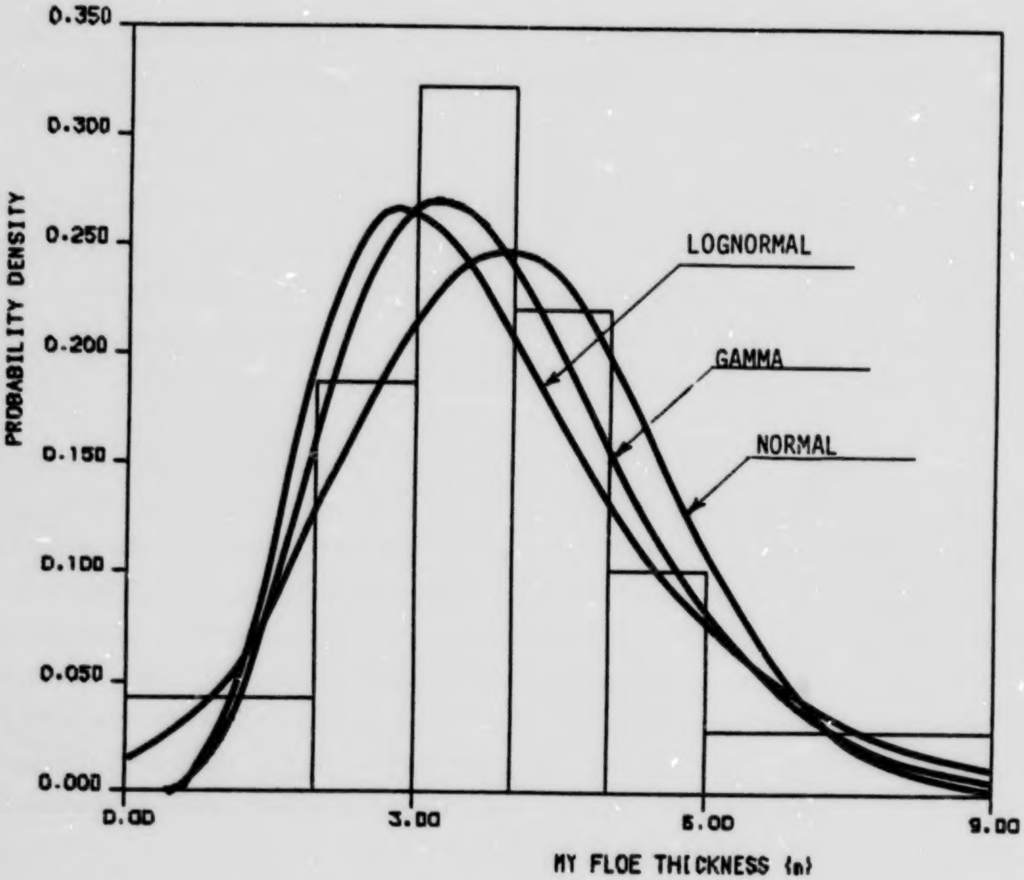


Fig. 3.2 Comparison Between Different Density Functions to Model Multi-Year Floe Thickness

Table 3.4

Results of Chi-Square Test for Multi-Year Floe Thickness

Distribution Type	Data Mean (m)	Data Standard Deviation (m)	Chi-Square Statistic	Level of Significance
Gamma *	3.89	1.584	1.549	0.671
Normal	3.89	1.584	3.198	0.362
Lognormal	3.89	1.584	4.150	0.245

* Selected model

Table 3.5

Season Boundary Values (Canadian Baufort Sea)

Transition	Mean Date	Standard Deviation (days)	Distribution Type	Data Source
Full cover to Partial cover	June 22	18.1	Normal	AES (1953-1984)
Partial cover to open water	July 6	22.9	Normal	AES (1953-1984)
Open water to Full cover	Nov. 5	22.8	Normal	AES (1953-1984)

Table 3.6

Ice Movement Speeds (Canadian Beaufort Sea)

Ice Conditions	Mean (m/s)	Standard Deviation	Distribution Type	Data Source
Full ice cover	0.062	0.073	Gamma	Murphy et al (1983)
Partial ice cover	0.042	0.042	Exponential	Oceanographic Services Inc. (1980)
Open water (all features)	0.17	0.13	Gamma	Marcellus & Morrison (1982) Danielewicz and Pilkington (1980)

Table 3.7

Landfast Full Ice Cover Peak Speed Parameters (Canadian Beaufort Sea) (Spedding, 1973, 1975, 1977)

Water Depth Range (m)	Average No. of Peaks/month	Mean Peak Speed (m/hr)	Standard Deviation (m/hr)	Distribution Type
0 - 6.1	11	.30	.20	Numerical
6 - 12.2	22	.31	.30	Numerical
12 - 18.3	111	.34	.25	Numerical
> 18.3	100	.55	.85	Numerical

Table 3.8

Geometric Properties of Different Ice Types (Canadian Beaufort Sea)

Ice Type	Parameter	Units	Mean	Standard Deviation	Distribution Type	Data Sources
MY floe	Thickness	m	3.9	1.6	Gamma	AIDJEX (1976)
	Diameter	km	0.1	0.15	Gamma	Spedding (1979), Weeks et al (1977)
	Ridge height*	m	.9	.9	Exponential	
	Ridge length	m	150	0	Deterministic	
	Ridge coverage	%	30	0	Deterministic	Weeks et al (1977)
Ice Island	Thickness	m	39.8	14.5	Numerical	De Paoli et al (1982), Dunwoody (1982)
	Diameter	km	12.5	7.1	Numerical	De Paoli et al (1982), Dunwoody (1983)
Ice Island Fragment	Thickness	m	39.8	14.5	Numerical	
	Diameter	m	70.0	43.0	Numerical	Spedding (1974, 1975), Barton et al (1972)
FY Ridge	Height*	m	0.9	0.9	Exponential	Wright and Schwab (1979)
	Length	m	130	0	Deterministic	
	Coverage	%	30	0	Deterministic	Weeks et al (1977)
Level Ice	Rate of growth	m/day	.0085	0	Deterministic	Richardson & Burns (1975)
	Max. thickness	m	1.5	0	Deterministic	

* Adjusted to cover whole range of parameter ($0 \rightarrow \infty$) as discussed in Sec. 3.5.

Table 3.9

Multi-Year Feature Coverage in the Canadian Beaufort Sea

Ice Type	Ice Conditions	Distance Offshore (km)	Parameter (Units)	Mean	Standard Deviation	Data Source
MY Floe	Full cover	all	Concentration (tenths)	0.2	0.4	AES (1953-84)
	Partial cover	all	"	0.2	0.4	"
	Open water	0-20	"	0.2	0.7	"
		20-40	"	0.3	1.0	"
		40-60	"	0.4	1.2	"
		60-80	"	0.6	1.6	"
		80-100	"	0.7	1.8	"
		100-120	"	0.9	2.0	"
		120-140	"	0.9	2.1	"
		140-160	"	1.3	2.4	"
Ice Island	all	all	Density (/km^2)	6.6×10^{-8}	0.	Dunwoody (1983)
Ice Island Fragment	all	all	Density (/km^2)	6.6×10^{-6}	0.	-

Table 3.10
Mechanical Ice Properties

Ice Type	Parameter	Units	Mean	Standard Deviation	Distribution Type	Data Sources
Multiyear Ice	Avg. pressure	MPa	0.5	0.5	Exponential	
	Flexural Strength	MPa	0.25	0.15	Normal	
	Poisson's Ratio	-	0.3	-	Deterministic	Hutter (1975)
	Elastic Modules	GPa	5.0	-	Deterministic	Lainey and Tinawi (1984)
First Year Ice (on Structure)	Avg. pressure	MPa	0.3	-	Deterministic	
	Extremal pressure	MPa	0.2	0.15	Double Expon.	
	Avg. Flexural Strength	MPa	0.2	-	Deterministic	
	Extremal Flexural Strength	MPa	0.1	0.05	Double Expon.	
	Poisson's Ratio	-	0.3	0.	Deterministic	
	Elastic Modules	GPa	5.0	0.	Deterministic	
	Creep Multiplier	MPa^{-3} s^{-1}	10^{-5}	-	Deterministic	Wang (1979)
	Creep Exponent		3		Deterministic	Sinha (1981)
First Year Ice (Ridge Building)	Pack Ice Pressure	MPa	0.05	0.05	Normal	Jordaan et al (1984)
FY Ridge	Rubble Friction Angle	Deg.	25	0.	Deterministic	Prodanovic (1981)
	Rubble Cohesion	MPa	0.035	0.	Deterministic	

3.6.3 Parameter Distributions for the Grand Banks

The Grand Banks are located east-south-east of Newfoundland in a region commonly bounded by gridlines 45-55° W and 45-55°N. A structure in this region would be exposed to icebergs and occasionally pack ice. Data regarding the necessary parameters values for these scenarios were reviewed and analyzed in the study. The results are discussed in the following.

a) **Icebergs**

The selected values of the basic parameters needed for calculation of the extremal load from iceberg collisions are summarized in Table 3.11. It is noted that only iceberg length (L) is given in the Table, whereas other geometric properties are needed for ice structure interaction calculations. These are the average iceberg contact diameter (A), iceberg mass (M) and central moment of inertia about the Z axis (I_z), see Fig. 3.3. These can be obtained from iceberg length based on geometric idealizations and statistical correlations between iceberg parameters. The geometric idealization made is to treat the iceberg as an ellipsoid. The height (H) and draft (D) of the iceberg which define the vertical dimension of the ellipsoid can be calculated from the length (L) using the relationships (Hotzel and Miller, 1982):

$$H = .4025\, L^{.89} \tag{3.1}$$

$$D = 3.781\, L^{.63} \tag{3.2}$$

The average waterline diameter L' is given by:

$$L' = \frac{L+W}{2} \tag{3.3}$$

Where

$$W = 0.7118L \tag{3.4}$$

The diameter at the contact level A can be related to L, based on information

Table 3.11

Iceberg Parameter Distribution (The Grand Banks)

Parameter	Units	Mean	Standard Deviation	Distribution Type	Data Source
Flux	berg /km	0.56	0	Deterministic	Ice Engineering (1983)
Length	m	121.6	56.7	Gamma	Ice Engineering (1981, 1982, 1983)
Velocity	m/s	.27	.32	Numerical	Mobil Oil Canada Ltd. (1973-1976)
Ice Pressure	MPa	3	3	Exponential	

regarding underwater profiles of icebergs from Benedict (1981), by:

$$A = L' + 2.106\, L^{.63} \tag{3.5}$$

Iceberg mass is calculated from (Hotzel and Miller, 1982):

$$M = 2.009\, L^{2.68} \quad \text{(M in tonnes)} \tag{3.6}$$

Iceberg inertia around the z axis is calculated by approximating the ellipsoidal shape in Fig. 3.3 by an elliptic cylinder with axes L and W, and height H + D.

It is noted that an average flux of 0.56 bergs/km.year is based on an average total of 418 icebergs crossing the 48° N-latitude between the 45° and 55° W longitude. The use of flux data to estimate collision rates reflects the assumption that the southerly drift component of iceberg movement is much larger than the random component of movement which is caused by storms.

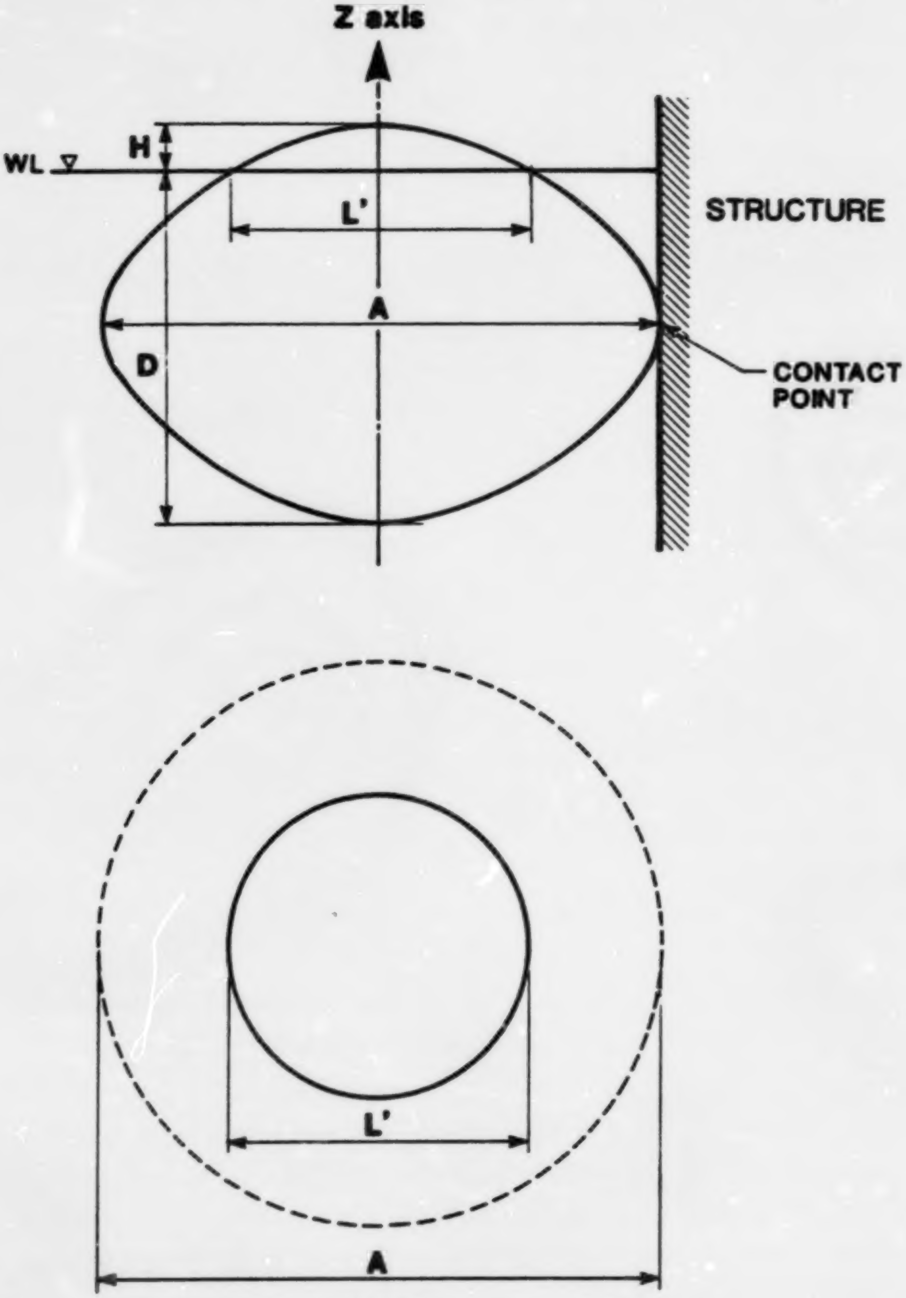

Z axis
H
WL
L'
STRUCTURE
A
D
CONTACT POINT
L'
A

Fig. 3.3 Iceberg Dimensions and Idealized Shape

b) Pack Ice

Information on sea ice was obtained from the Atmospheric Environmental Services data base system CRISP. This information is summarized in Fig. 3.4 for the period 1963 to 1984. The frequency of occurrence of sea ice, the beginning and end dates of its presence and the concentration of ice when present are summarized in Table 3.12.

Considering that the maximum ice thickness is 1m and that this is warm first year ice, it is not expected that loading from this ice will be significant in comparison to iceberg loads. It is therefore suggested that pack ice forces be neglected in the Grand Banks area.

If, however, the user wishes to consider this scenario, distinction should be made between two different ice conditions separated by the dates given in Table 3.12. The average ice concentration in the table suggests that in the presence of pack ice, partial ice cover conditions prevail. It is noted that most icebergs occur in the spring and the partial ice cover season will therefore contain level ice as well as iceberg loading scenarios. The remainder of the year will consist of open water conditions during which the rest of iceberg flux will represent the only hazard.

Table 3.12

Pack Ice Data Summary for the Grand Banks Region

(AES - CRISP System)

Parameter	Units	Mean	Standard Deviation
Probability of Occurrence	%	38	-
Start Date	-	February 21	20.
End Date	-	April 1	16.
Concentration	tenths	6.8	2.3

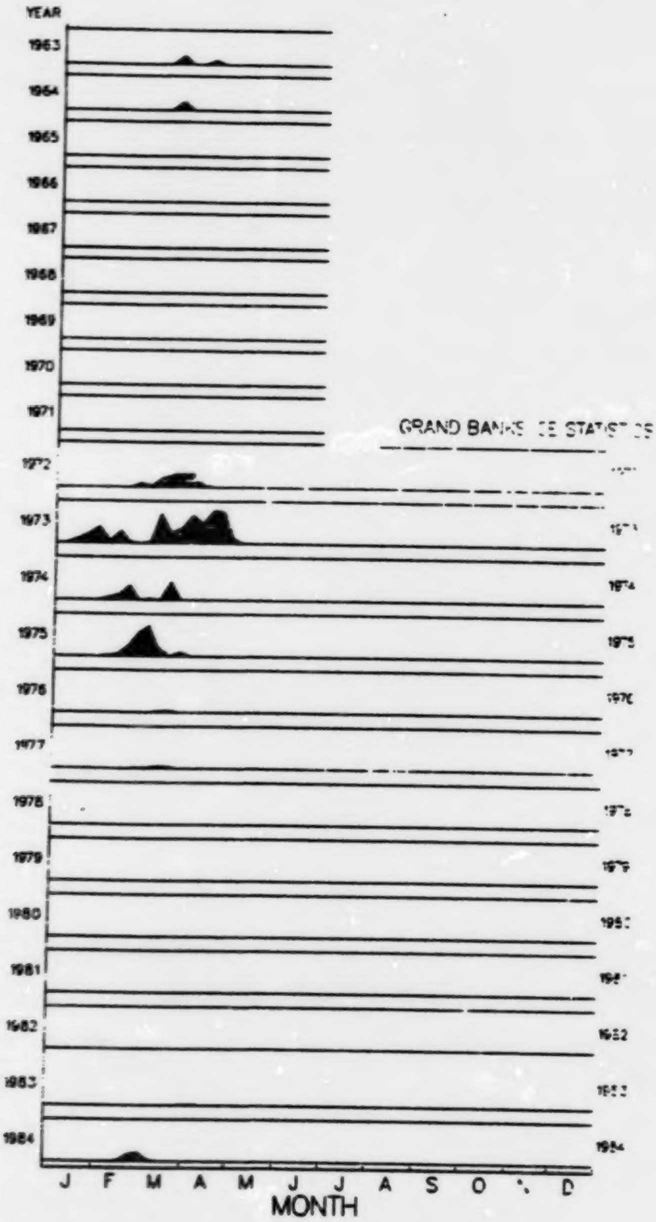


Fig. 3.4 Summary of Pack Ice Concentration Data in the Grand Banks Region

CHAPTER 4

ICE-STRUCTURE INTERACTION MODELS

4.1 General

Although the focus of the study is on probabilistic approaches, the probabilistic model cannot be operational without the appropriate force calculation models. These models were developed using state-of-the-art methods in ice-structure interaction and are included in separate modules in the final model and program in order to facilitate modification or replacement if desired. The selection criteria for these models were: a) realistic representation of the actual ice-structure interaction phenomena, and b) simplicity. The need for simplicity is related to the practicability of applying these models in probabilistic analyses and Monte Carlo simulations.

The purpose of this chapter is to summarize the ice-structure interaction failure modes and load calculation approaches developed and used in the model. Detailed reviews of some of the approaches used can be found in Nessim et al. (1984, 1986, 1987). New models were developed for areal ice feature collisions in open and closed water collisions.

The maximum force on the structure can be governed by one of the two following conditions (Croasdale, 1980):

a) The structure introduces sufficient forces to stop the ice or change its direction of motion such that it loses contact with the structure. This is a global consideration which requires modelling the ice movement under the environmental driving forces and the forces exerted on the ice by the structure.

b) If the driving forces are sufficiently high, the condition described in a) above may not be reached before the structure is fully enveloped in the ice feature. In this case the contact width is at its maximum value and the local indentation problem reaches its steady-state maximum load. Any further energy dissipation will occur at the same load level, and the maximum load can therefore be calculated from a local model.

In the following, local load models will be used for first year level ice and first year ridge scenarios during which maximum local loads are normally reached. For areal ice feature interactions, global models are needed because of the high likelihood that maximum local forces will not be reached. Global models are used for areal features in open water, as well as partial and full ice cover conditions. It is noted that the solution of a global model requires a local model for calculating the force between the ice and the structure at any global configuration. This is illustrated in Fig. 4.1. In the following, local and global force models will be discussed in Sec. 4.2 and 4.3.

4.2 Local Force Models

The choice of an appropriate local ice force model depends on the mode of ice deformation (or failure mode) which is in turn governed by the material behaviour of ice and the interaction geometry. The dominant deformation (or failure) modes for different conditions are summarized in Table 4.1. It must be noted that in many cases the actual behaviour of ice is a combination of several failure modes and that the information in Table 4.1 gives the dominant modes which are used in theoretical calculation models. The approaches used in calculating the force for different cases are discussed in the following sections.

4.2.1 Ice Sheets

4.2.1.1 Vertical Structures

This type of interaction is illustrated in Fig. 4.2 and is referred to as the indentation problem. The model used depends on the interaction speed:

a) Slow Interactions typical of landfast zone movements, and occasionally occuring in the pack ice zones are dominated by creep. The ice flows around the structure and does not fail. The secondary creep law for ice is given by (Sinha, 1981):

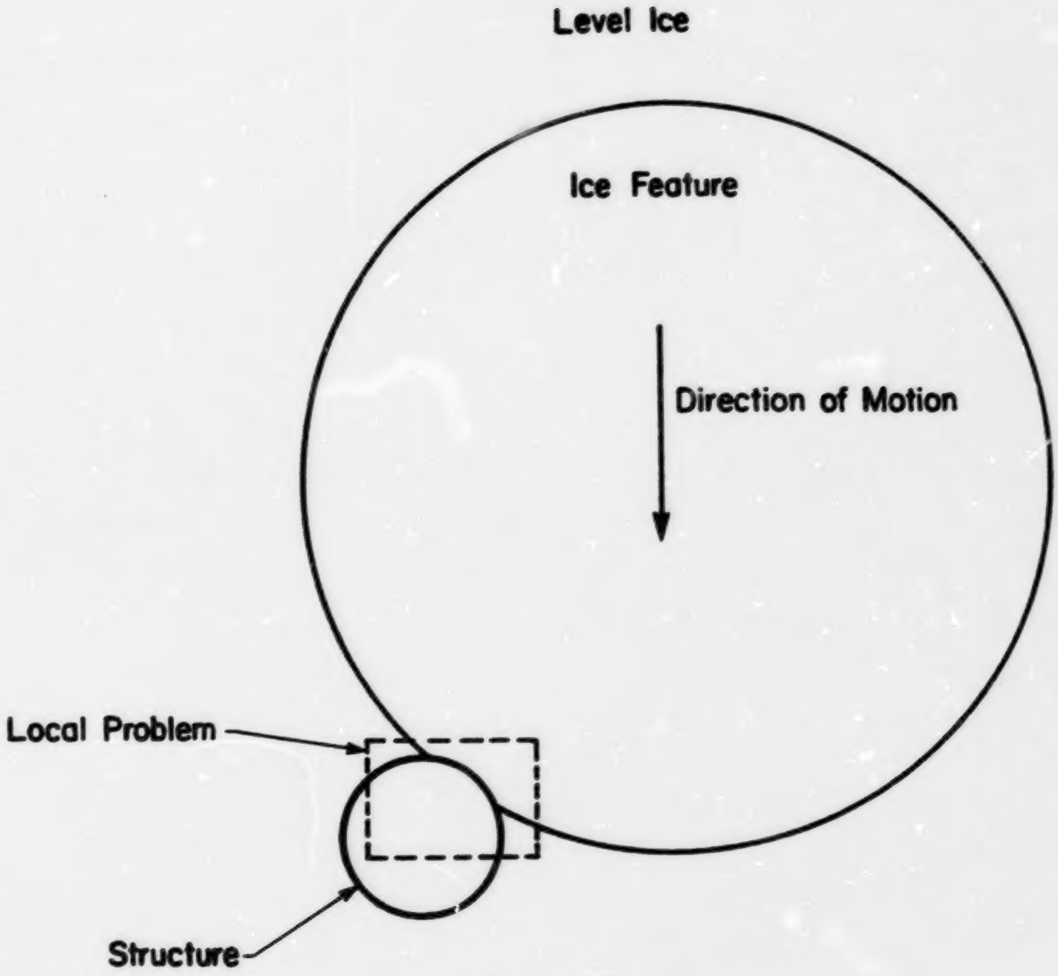

Level Ice
Ice Feature
Direction of Motion
Local Problem
Structure

Fig. 4.1. Illustration of Global and Local Force Models

Table 4.1
Dominant Ice Deformation Modes for Different Interaction Conditions

Structural Geometry	Loading Rate	Ice Type				
		FY Level Ice	FY Ridge	MY Floe	Ice Island or Island Fragment	Iceberg
Vertical	Fast	Crushing bending or buckling	Rubble shear or crushing	Crushing bending or buckling	Crushing	Crushing
	Slow	Creep	Rubble shear or crushing	-	-	-
Sloping	Fast	Bending	Rubble shear or crushing	Bending/ crushing	Bending/ crushing	-

$$\dot{\varepsilon} = A\sigma^n \tag{4.1}$$

where $\dot{\varepsilon}$ is the strain rate;

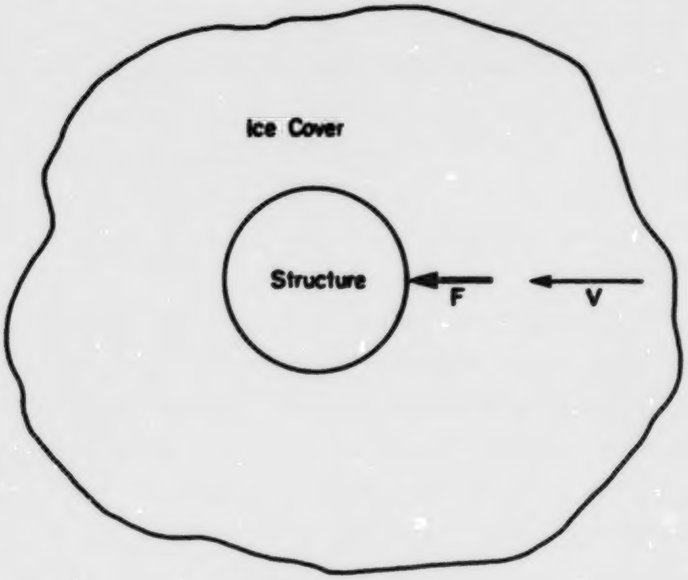
σ is the stress; and

A,n are the creep constants of ice.

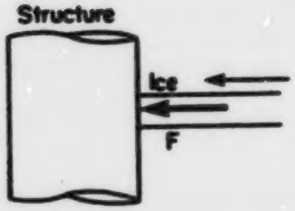
Experimental evidence (Sinha, 1981, and Lainey and Tinawi, 1984) indicates that n = 3 and that $A = 10^{-5}\,(\text{MPa})^{-3}\,\text{sec.}^{-1}$.

A simple and accurate creep solution can be obtained using the reference stress method (Ponter et al., 1983). In general, the force F on the structure at a given ice movement speed v can be calculated from the equilibrium condition given as:

$$Fv = \int_V \sigma_{ij}\dot{\varepsilon}_{ij}\,dV \tag{4.2}$$


Ice Cover
Structure
F
V

(a) Plan View


Structure
Ice
F

(b) Elevation

Fig. 4.2. Ice Sheet Movement Against a Vertical Structure

where σ_{ij} is the stress tensor;
$\dot{\varepsilon}_{ij}$ is the strain rate tensor;
V is the volume; and
the relationship between σ_{ij} and $\dot{\varepsilon}$ is given by the creep law in Eq. (4.1)

The essence of the reference stress method is to approximate Eq. 4.2 by:

$$Fv = \sigma_R \, \dot{\varepsilon} \, (\sigma_R) \, V_R \tag{4.3}$$

where σ_R is defined as the reference stress, V_R is defined as the reference volume, and $\dot{\varepsilon}(\sigma_R)$ is the actual creep law of the material considered (Eq. 5.1). The values of σ_R and V_R can be evaluated from the solutions of two problems with the same geometry as the problem considered, but with two different constitutive laws of the creeping material. These constitutive laws need not include the actual creep law for ice. Equation (4.3) can be rearranged in the form:

$$F = \phi \; Dt \; \sigma \; \left(\frac{v/D}{\phi\psi}\right) \tag{4.4}$$

where D is the width of the structure, and t is the ice thickness. In this rearranged form, the constants needed to have a solution for a given geometry are the non-dimensional coefficients ϕ and ψ. For a circular structure embedded in level ice with $T << D$ (i.e. plane stress problem $\phi = 1.174$ and $\psi = 0.42$. The use of these values and of Eq. 4.1 into Eq. 4.4 gives a general solution of the problem for any combination of v, D and t (provided that plane stress conditions apply).

b) Fast Interactions are typical in pack ice zones and for free floating areal features. The ice behaviour in fast interactions with vertical structures depends on the geometry of contact. For wide structures and thin ice (e.g. floes), several phenomena take place including localized crushing, bending and ride-up. For icebergs, crushing (pulverization) can be expected to dominate the interaction due to the high confinement of the ice. Cracking also plays a role in fast interaction and the possibility of global fracture exists. In the absence of adequate models which can account for all of the above phenomena, a constant average indentation presure is used for each interaction event. A random component is added to this pressure to account for random variations, and this will be described in detail in Sec. 5.1.3 and 5.4.2 where statistical models are addressed. This average pressure should be estimated from field data under similar conditions to the case being considered. Given the pressure value σ, the ice force F can be calculated from:

$$F = \sigma Dt \tag{4.5}$$

where t is the ice thickness and D is the contact width. The calculation of the contact width is demonstrated in Fig. 4.3.

4.2.1.2 Sloping Structures

Ice fails in bending against sloping structures. The bending resistance of ice is not a basic property, but is a manifestation of its tensile resistance. Since sloping structures in the landfast ice zone are not considered, loading in bending will mostly be at relatively high rates at which elastic ice behaviour is dominant. After bending failure a ride-up phase begins during which the broken ice pieces move up (or down for downward breaking) the cone until the ice sheet comes into contact with the structure again. This sequence is illustrated in Fig. 4.4.

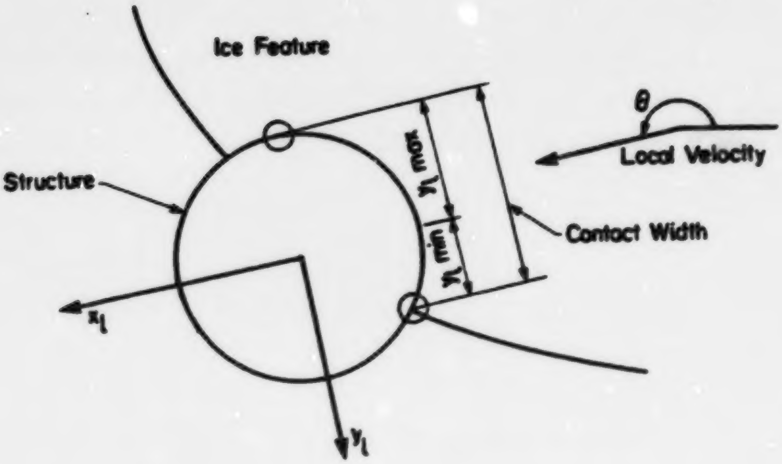
The horizontal and vertical, ride-up forces on the structure F_{H_r} and F_{V_r} are given by:

$$F_{H_r} = w \cos\alpha \, (\sin\alpha + \mu \cos\alpha) \tag{4.6}$$

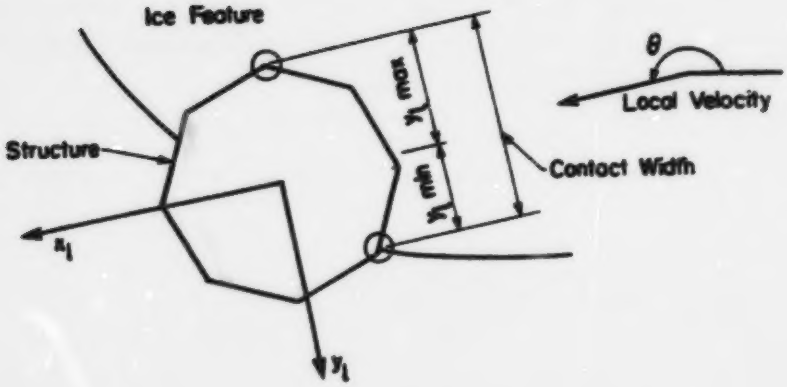
$$F_{V_r} = w \cos\alpha \, (\cos\alpha - \mu \sin\alpha) \tag{4.7}$$

where w is the ride-up weight (or uplift for downward breaking cones), α is the cone angle to horizontal and μ is the friction coefficient between ice and the structure. The maximum ride-up force on a cone occurs when half the cone is covered by ice giving a maximum ride-up weight of:

$$w = \frac{\pi t}{\cos\alpha} \left(2R_w \, H/\tan\alpha - (H/\tan\alpha)^2 \right) \gamma_i \tag{4.8}$$

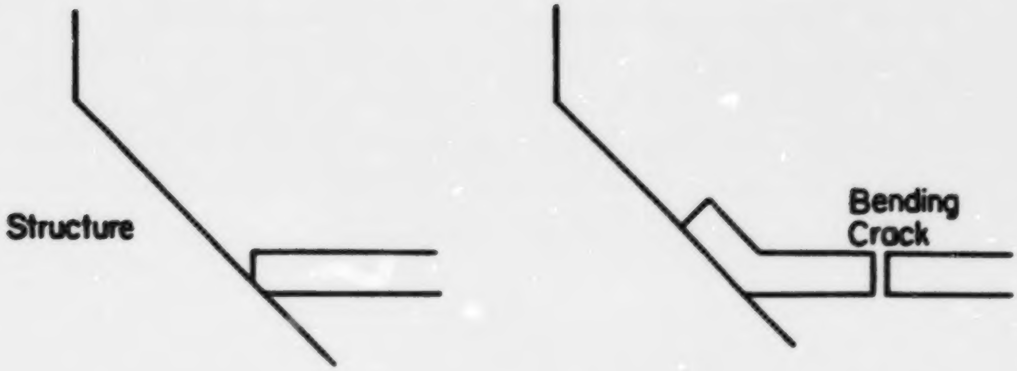

Ice Feature
θ
Local Velocity
Structure
y_l max
y_l min
Contact Width
x_l
y_l

(a) Circular structure


Ice Feature
θ
Local Velocity
Structure
y_l max
y_l min
Contact Width
x_l
y_l

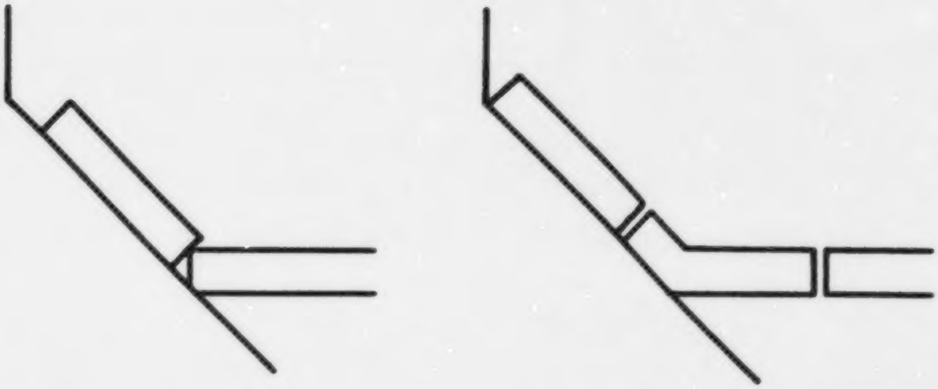
(b) Polygonal structure

Fig. 4.3. The Contact Width Between a Vertical Structure and Ice Sheet


Structure
Bending
Crack

(a) Initial Crushing

(b) Ride-up



(c) Subsequent Crushing

(d) Subsequent Ride-up

Fig. 4.4. Interaction Process Between an Ice Sheet and a Sloping Structure

where t is the ice thickness, R_w is the water line radius of the cone, H is the cone freeboard, α is the cone slope to the horizontal, and γ_i is the weight of ice per unit volume. For a downward breaking cone, γ_i is to be replaced by $\gamma_w - \gamma_i$, where γ_w is the weight of water per unit volume.

At the point of breaking of the next ice piece, the breaking force should be added to the ride-up force to give the total force on the structure. The vertical breaking force F_{V_b} can be calculated from the theory of plates on elastic foundations as (Croasdale, 1980):

$$F_{V_b} = 0.68\ \sigma_f\ \left(\frac{\gamma_w t^5}{E}\right)^{1/4} \ell_b \tag{4.9}$$

where σ_f is the flexural strength of ice, γ_w is the specific weight of water, E is the modulus of elasticity for ice, t is the ice thickness, and ℓ_b is the breaking length of ice. The length, ℓ_b, can be expressed as:

$$\ell_b = \pi\ \left(\frac{b}{2} + \frac{\pi}{4}\ \ell_c\right) \tag{4.10}$$

where b is the contact width and ℓ_c is the characteristic length given by:

$$\ell_c = \left(\frac{Et^3}{12\gamma_w\ (1-\nu)^2}\right)^{1/4} \tag{4.11}$$

and ν is Poisson's ratio for ice. The corresponding horizontal force F_{H_b} is given by:

$$F_{H_b} = F_{V_b} \cdot \tan\alpha \tag{4.12}$$

4.2.2 First Year Ridge (Ice Rubble)

Ice rubble behaves like a granular material (Prodanovic, 1981). The shear strength (τ) of ice rubble can be expressed as a function of its cohesion c and angle of friction ϕ as follows:

$$\tau = c + \sigma \tan\phi \tag{4.13}$$

where σ is the normal stress on the shear plane. The normal stress σ is equal to the passive resistance of the material (Gregory and Tschekotarrioff, 1973) given by:

$$\sigma = p \tan^2(45° + \frac{\phi}{2}) + 2c \tan (45° + \frac{\phi}{2}) \tag{4.14}$$

where p is the vertical "overburden" pressure, ϕ is the material friction angle, and c is the cohesion. For the ridge sail, the vertical pressure at any point is equal to the weight of the ice $\gamma_i h$, where γ_i is the ice weight per unit volume and h is the depth from the top ice surface. For the keel, the vertical pressure is due to the difference between the buoyancy and the weight, and is equal to $(\gamma_w - \gamma_i)d$, where γ_w is the weight of water per unit volume, and d is the height from the bottom surface of the ice.

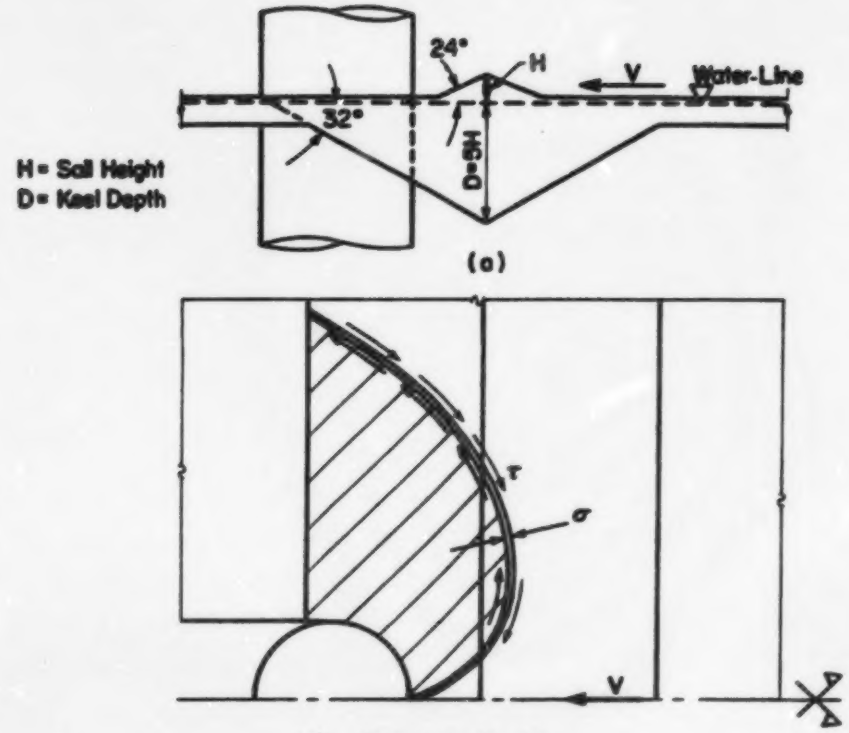
An idealized first-year ridge cross section is shown in Fig. 4.5 (a) (Prodanovic, 1979). As a Columb-Mohr material, the rubble can fail in one of the two modes shown in Fig. 4.5 (b) and (c), namely crushing or shear. An upper bound force on the structure due to rubble crushing can be calculated by postulating a clearing mechanism such as the one shown in Fig. 4.5 (b) and finding the force necessary to shear the ice along the boundary of the clearing ice. For the shearing failure shown in Fig. 4.5 (c), the force on the structure is simply equal to the integral of the shearing stresses along the two shear planes.

For cones, the horizontal force F_H is calculated as above using the average contact diameter between the cone and the ice ridge. The vertical force F_V is then calculated on the basis of a no-friction assumption as:

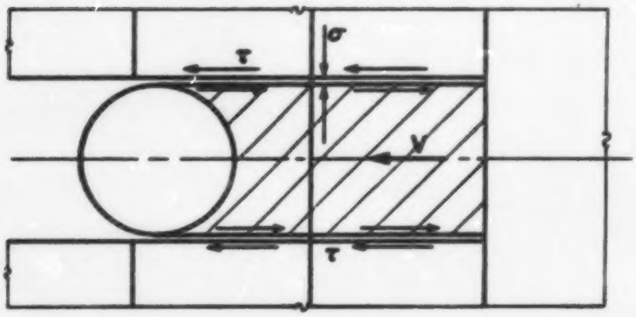
$$F_V = F_H/\tan \alpha \tag{4.15}$$

where α is the cone slope angle.

The results of the model used to calculate forces from first-year ridges on the structure are illustrated in Fig. 4.6. The figure shows the force penetration curves for the interaction of a ridge which has a 2-m high sail with the two structures shown. The rubble cohesion used is .035 MPa (Prodanovic, 1981), and the friction angle of the


24°
H
V
Water-Line
32°
H = Sail Height
D = Keel Depth
D=5H
(a)
τ
σ
V

(b) Failure by Crushing



(c) Failure by Shear

Fig. 4.5. Idealized First-Year Ridge Cross Section and Failure Mechanisms

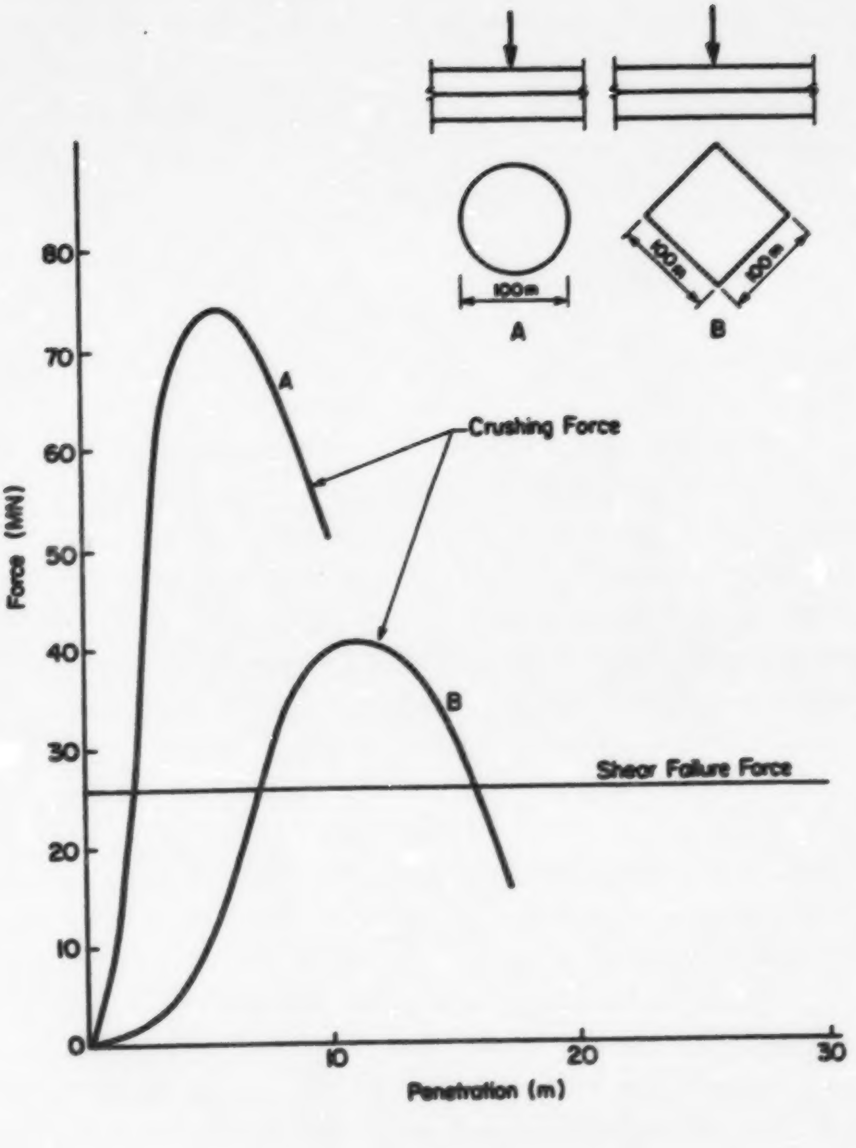


Fig. 4.6. Sample Result of First-Year Ridge Forces on Vertical Structures

rubble is 25°. It can be seen that the rubble-crushing force rises faster, and reaches a higher value in the case of the circular structure than for the case of the square structure. This is due to the high rate of increase of contact width with the penetration for the circular structure. The drop of the force value in each case starts once the discontinuity surface passes the thickest point on the ridge (see Fig. 4.5). It can also be seen that the shear failure force is less than the maximum rubble-crushing force for both structures and thus, shear is the governing mechanism in these two examples.

4.3 Global Force Model

4.3.1 General

Global force models are needed for discrete areal ice feature interactions (i.e. floes, icebergs and ice islands) in order to take into account the force limitations due to eccentricity of the impact. During eccentric impacts part of the initial kinetic energy would be transformed into rotation and the floe could clear before the maximum local force is reached. To ignore this effect would lead to the overestimation of impact forces especially for open water impacts where the feature is free to rotate and clear thus reducing the portion of energy dissipated in local deformation. The problem is illustrated in Fig. 4.7 where F_b represents the total force on the feature from the surrounding first year ice (for open water $F_b = 0$).

Even with simple assumptions regarding the constitutive behaviour of ice the problem is non-linear. There is a geometric non-linearity which results from the interdependence between the local force and the movement of the ice feature. This non-linearity can be modelled by solving the equations of motion in an iterative, time stepping algorithm (Nessim et al, 1986). This approach can be used to solve the problem for both open water and closed water conditions. It can be appreciated, however, that such solutions require large computation times and are, therefore, too detailed for probabilistic analyses where a large number of interactions need to be simulated. Approximate solutions were therefore investigated for the purpose of this study and their results compared to the detailed time stepping solutions available at DnV. The results of this analysis are described in the following sections.

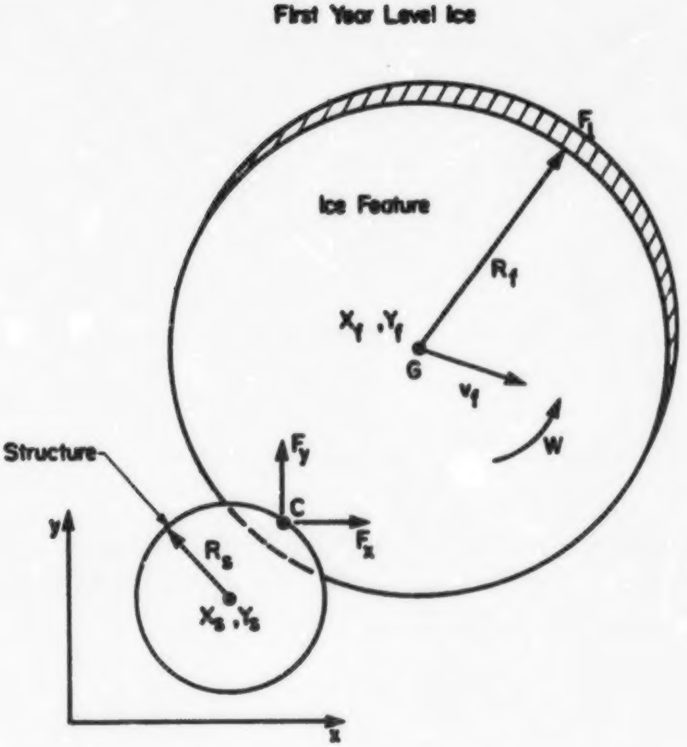

First Year Level Ice
F_i
Ice Feature
R_f
X_f, Y_f
G
v_f
W
Structure
F_y
C
F_x
y
R_s
X_s, Y_s
x

Fig. 4.7. Areal Ice Feature Collision With a Structure

4.3.2 Open Water Impacts

This approach was proposed by Nevel (1986). Consider an ice feature with mass m (including hydrodynamic added mass) and velocity v impacting a structure as shown in Fig. 4.7 but without the force F_b (open water conditions). The equations of motion are:

$$F_x = m\,x^{\cdot\cdot} \tag{4.16}$$

$$F_y = m\,y^{\cdot\cdot} \tag{4.17}$$

$$F_x\,(y_G - y_C) - F_y\,(x_G - x_C) = I\,\theta^{\cdot\cdot} \tag{4.18}$$

where I is the polar moment of inertia. Substituting Eqs. 4.16 and 4.17 into 4.18 leads to:

$$m\,x^{\cdot\cdot}\,(y_G - y_C) - m\,y^{\cdot\cdot}\,(x_G - x_C) = I\,\theta^{\bullet} \tag{4.18}$$

Assuming further that the ice feature clears when the point of contact C becomes the centre of rotation, and observing that, for a small rotation, $x^{\bullet} = \theta^{\bullet}\,(y_G - y_C)$ and $y^{\bullet} = \theta^{\bullet}\,(x_G - x_C)$ Eq. 4.20 leads to:

$$\theta^{\bullet} = \frac{-\,m\,v\,(x_G-x_C)}{I+m\,(\,(y_G-y_C)^2 + (x_G-x_C)^2\,)} \tag{4.21}$$

Thus the total rotational energy is given by:

$$E_r = \frac{m^2 v^2\,(x_G-x_C)}{2(\,I+m(y_G-y_C)^2 + m(x_G-x_C)^2\,)} \tag{4.22}$$

The total initial kinetic Energy $E_k = ½\,mv^2$ and the energy spent in local deformation is:

$$E_\ell = E_k - E_r \tag{4.23}$$

The problem is therefore reduced to a concentric impact with total energy E_ℓ. If the local force and energy can be defined as functions of the penetration F(P) and E(P), then the penetration P_ℓ corresponding to E_ℓ can be found and the maximum force can be calculated as the maximum of the function F(P) between $P = 0$ and $P = P_\ell$. This requires an iterative procedure. The relationships F(P) and E(P) will be addressed in Sec. 4.3.4.

The assumptions used in the above derivation are all reasonable and one would expect the error in the solution to be small. Comparison was made between this approximate solution and a detailed time stepping algorithm previously developed by DnV. The comparison is made for a multiyear floe 1 km in diameter and 5 m thick moving at a velocity of 0.25 m/s. The average pressure is assumed to be 0.5 MPa. Three structures are used:

a) a circular vertical sided structure 100 m in diameter;

b) a square vertical sided structure 100 m in width;

c) an upward breaking cone with 70 m waterline diameter, 20 m freeboard, and 60° slope to horizontal.

The results are shown in Figs. 4.8 to 4.10 and indicate that the two solutions compare extremely well especially for vertical sided structures where the two solutions coincide. For the cone example used the approximate solution is slightly conservative for the the mid-range eccentricities.

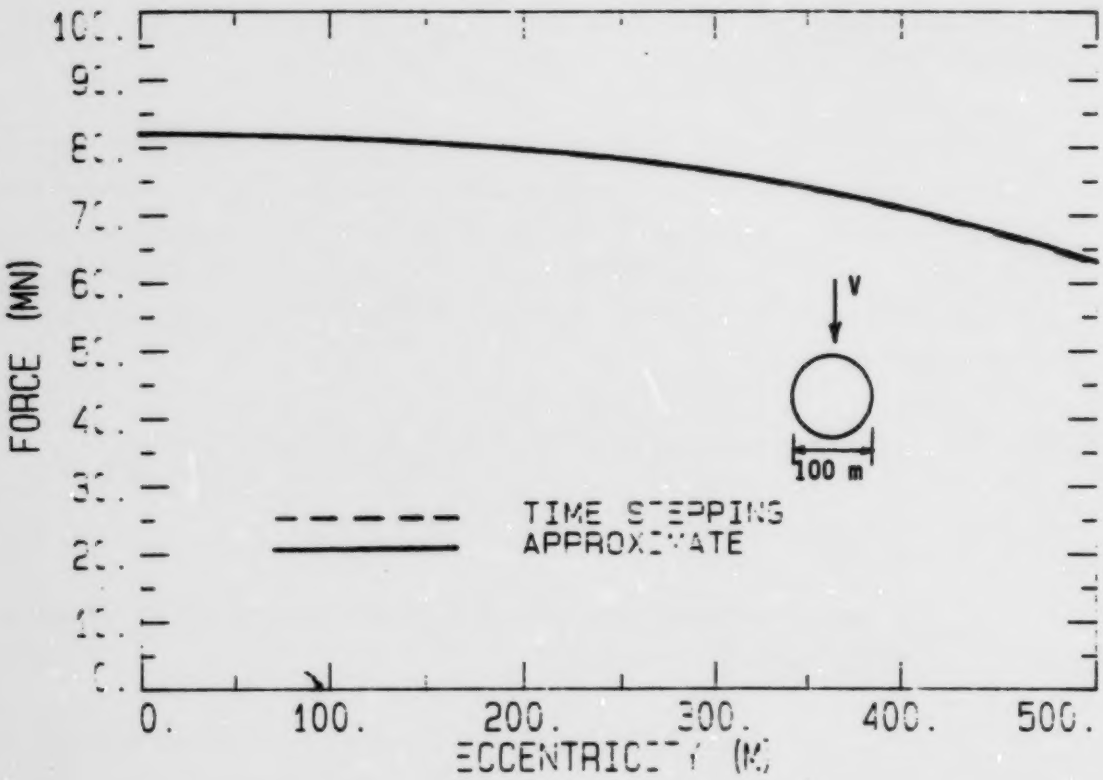


Fig. 4.8. Comparison Between Time-Stepping and Approximate Solutions for Vertical Circular Structure

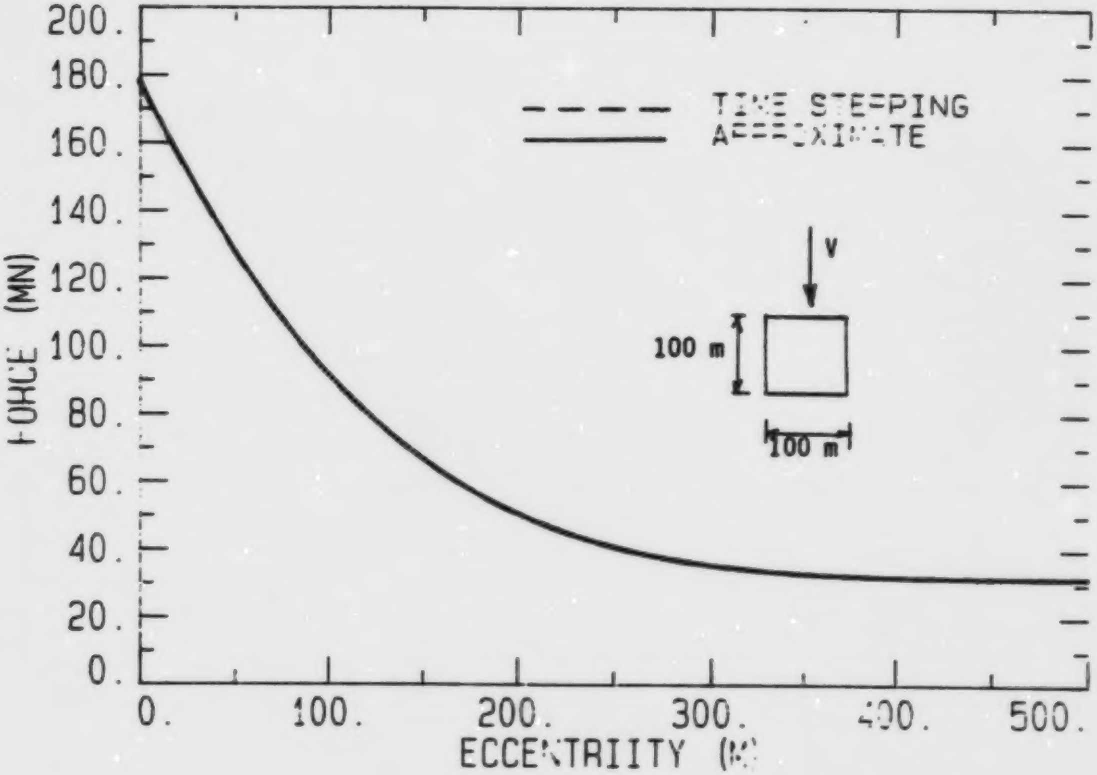


Fig. 4.9. Comparison Between Time-Stepping and Approximate Solutions for Vertical Polygonal Structure

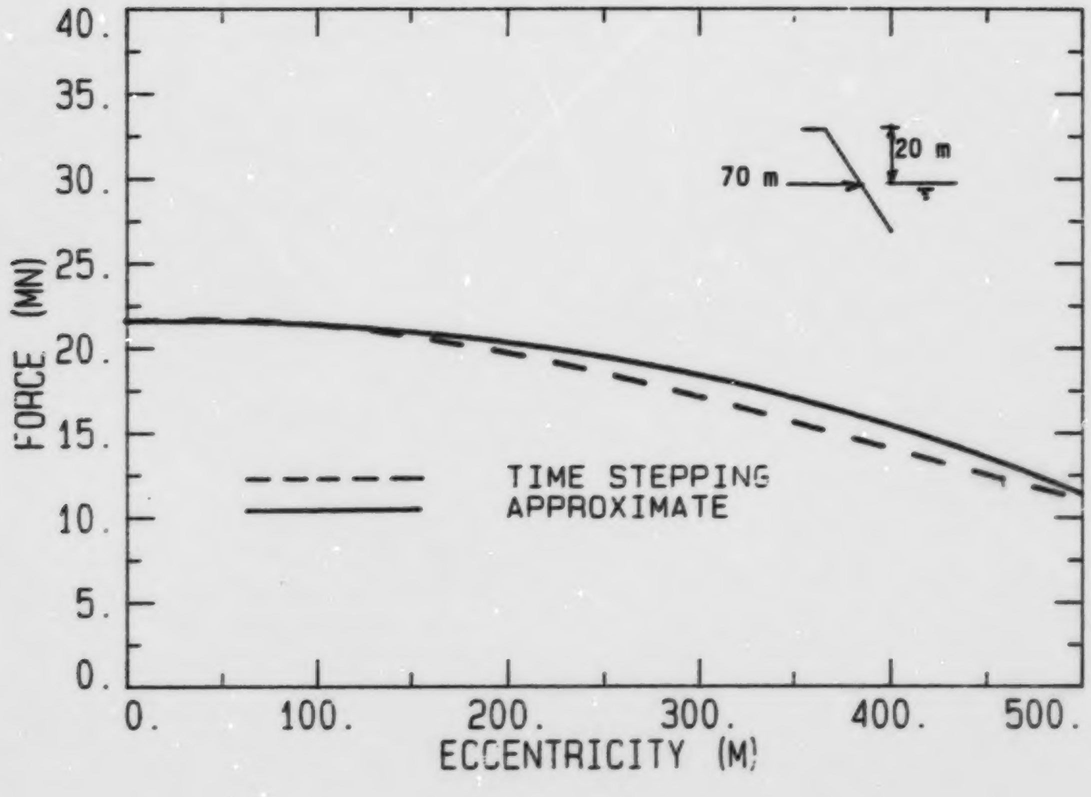


Fig. 4.10. Comparison Between Time-Stepping and Approximate Solutions for Conical Structure

4.3.3 Closed Water Impacts

For full and partial ice cover conditions, the above methodology is not applicable because the system is non-conservative due to the force applied to the ice feature by the surrounding level ice. It was, therefore, not possible to find a simple closed form solution to the problem in this case. As a conservative solution, the reduction in force due to eccentricity was not taken into account. It is noted that the influence of eccentricity on the maximum force from closed water impacts is much less significant than that for open water impacts. This is due to the confinement introduced by the surrounding ice which restricts the feature's rotation and clearing. This is illustrated in Table 4.2 for a floe 1 km in diameter and 5 m in thickness with an average ice pressure of 0.5 MPa. The floe is surrounded by 1 m thick first year ice which can impose a maximum pressure of 0.05 MPa. Using a detailed time stepping model the forces obtained for different eccentricities and their % reduction from a concentric impact are shown in Table 4.2. The table shows that for a maximum eccentricity equal to ½ the floe diameter the reduction in force is 12% and that the average reduction for all eccentricities is 4%.

Table 4.2
Effect of Eccentricity on Closed Water Impact Forces

Eccentricity	0 m	125 m	250 m	375 m	500 m	Average
Force (MN)	95.1	94.7	93.1	90.0	83.6	91.3
% Reduction in Force	0.0	0.4	2.1	5.4	12.1	4

The interaction in this case consists of two steps. Initially, the ice feature is frozen into the level ice and moving with it at the same speed. When it comes into contact with the structure, the local contact force F_c builds up. The force imposed by the level ice on the floe increases accordingly, to equilibrate F_c and this occurs at a constant velocity. The second phase begins when F_c reaches F_b which is the maximum force that can be imposed by the surrounding ice on the feature (ridge building forces for large features). The ice floe then breaks out of the pack ice and begins to decelerate. The equilibrium equation at the end of the first phase is:

$$F_b = F(P_0) \tag{4.24}$$

from which the penetration at break-out P_0 can be calculated. The energy balance equation at the end of the second phase is:

$$F_b\,(P - P_0) + E_k = E(P) - E(P_0) \tag{4.25}$$

where P is the final penetration, E_k is the floe kinetic energy at break-out and E(P) is the total dissipated local energy. Eq. 4.25 assumes that F_b is constant. The equation can be solved iteratively for P which can be used to find the maximum force.

4.3.4 Force-Penetration and Energy-Penetration Relationships

As mentioned in Secs. 4.3.2 and 4.3.3, the calculation of the maximum force on the structure during impact with a discrete areal feature requires the definition of the local force and the local energy dissipation as functions of the penetration of the structure into the ice. This depends on the principal local interaction mode and is thus dealt with separately for vertical sided and conical structures.

4.3.4.1 Vertical Structure

The energy is assumed to be dissipated in crushing, and the crushing energy equals the work done by the local force F. Thus:

$$E_{cr} = {}_0\int^P F \; d \; P \qquad (4.26)$$

The force is given by:

$$F = A(P) \cdot \sigma \qquad (4.27)$$

where A is the projected contact area perpendicular to the direction of motion and σ is the local pressure. Substituting Eq. 4.27 into Eq. 4.26 leads to:

$$E_{cr} = V(P) \cdot \sigma \qquad (4.28)$$

where V is the crushed volume.

Equations 4.27 and 4.28 represent the needed force and energy dissipation reduced to linear functions of the contact area and crushed volume respectively. Area and volume can be determined from the contact geometry as functions of the penetration (see Fig. 4.11).

Examples of the results of the computer models developed to calculate the force penetration-energy relationships are illustrated in Figs. 4.12 and 4.13 for a 100 m diameter circular structure, and 100 m wide square structure respectively. The ice feature used is a multiyear floe 1 km in diameter and 5 m thick with an average pressure of 0.5 MPa.

4.3.4.2 Conical Structures

A force history for interaction between a multiyear floe and a downward breaking cone is shown in Fig. 4.14. This is obtained from a detailed time stepping model (Nessim, 1986). The figure shows a gradual force increase on which sharp force peaks are superimposed. The gradual increase represents the ride-up force component which is present throughout the interaction and can be calculated from Eqs. 4.6 and 4.7. The sharp peaks represent the force necessary to break the ice in bending (given by Eq. 4.9). These peaks occur when a new piece of ice comes into contact with the

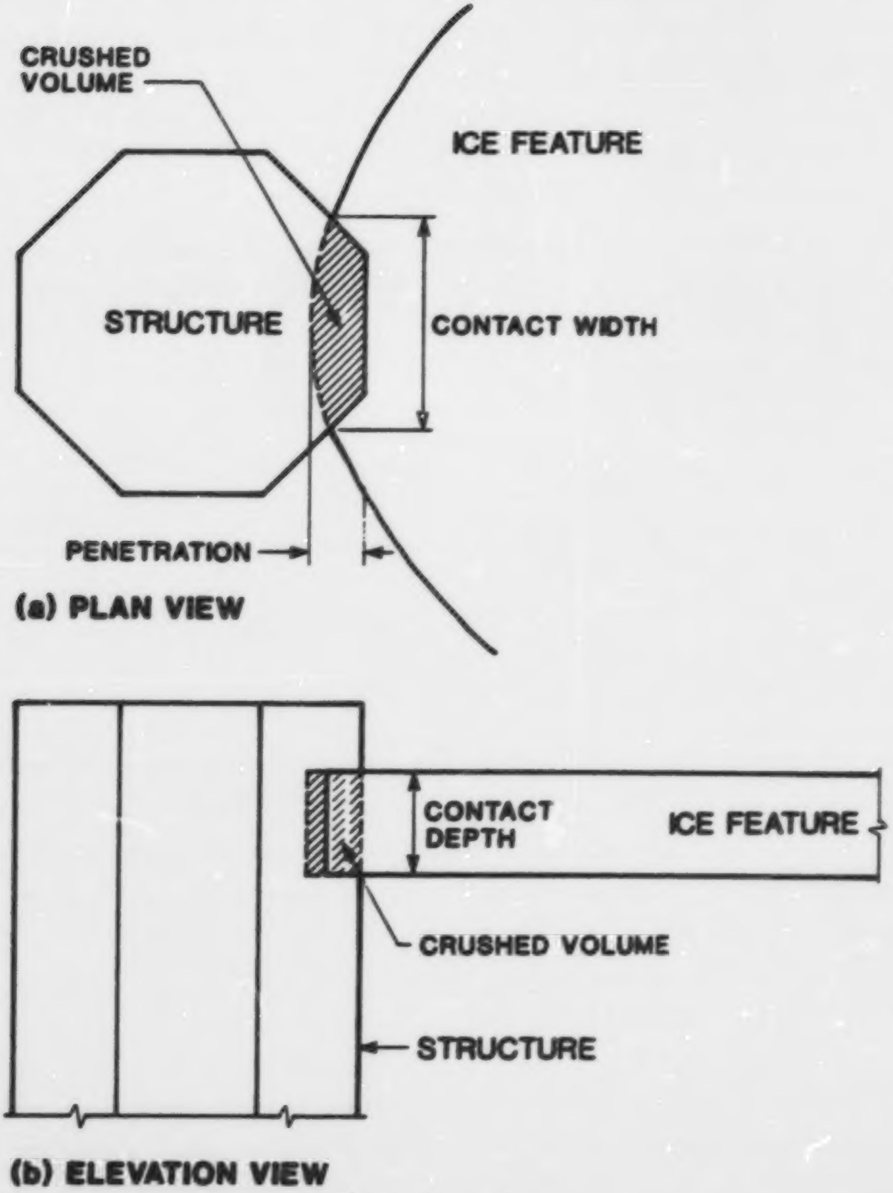

CRUSHED VOLUME
ICE FEATURE
STRUCTURE
CONTACT WIDTH
PENETRATION
(a) PLAN VIEW
CONTACT DEPTH
ICE FEATURE
CRUSHED VOLUME
STRUCTURE
(b) ELEVATION VIEW

Fig. 4.11. Illustration of Contact Geometry

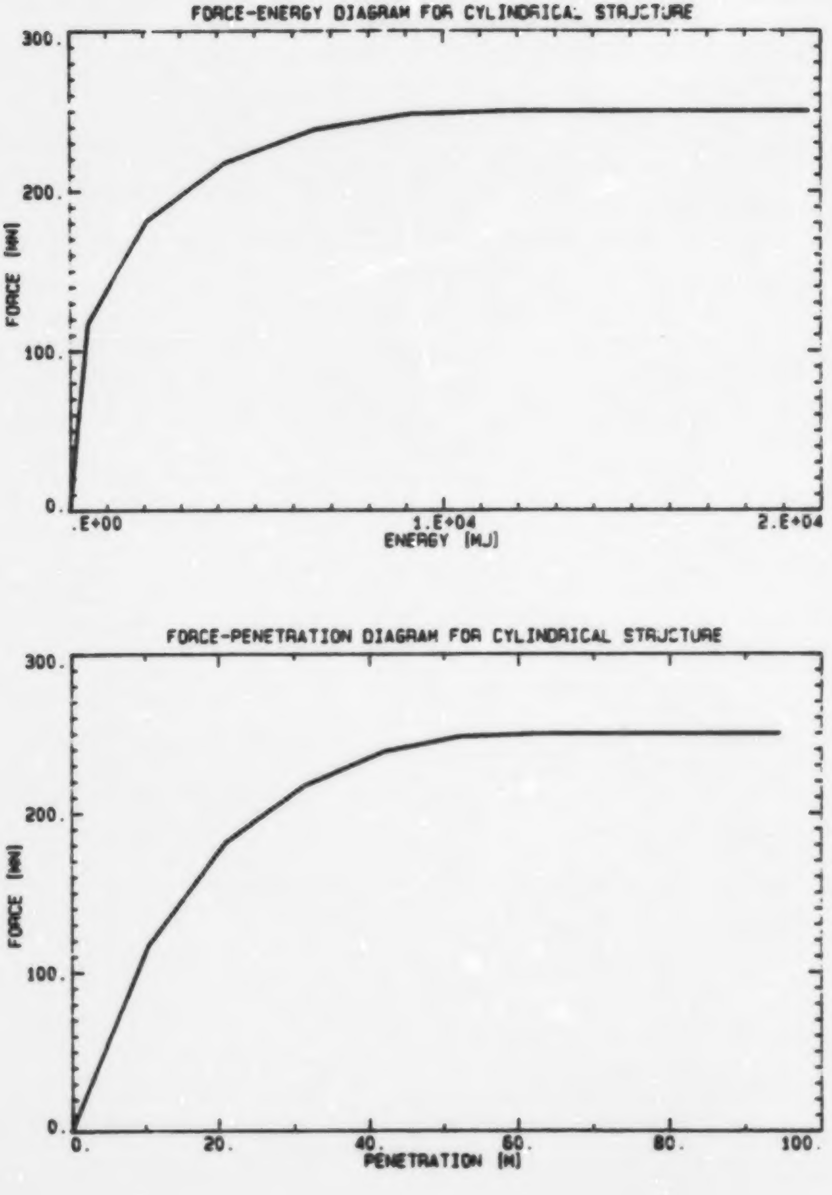


Fig. 4.12. Results of Penetration-Force-Energy Model for Vertical Circular Structure (diameter = 100 m)

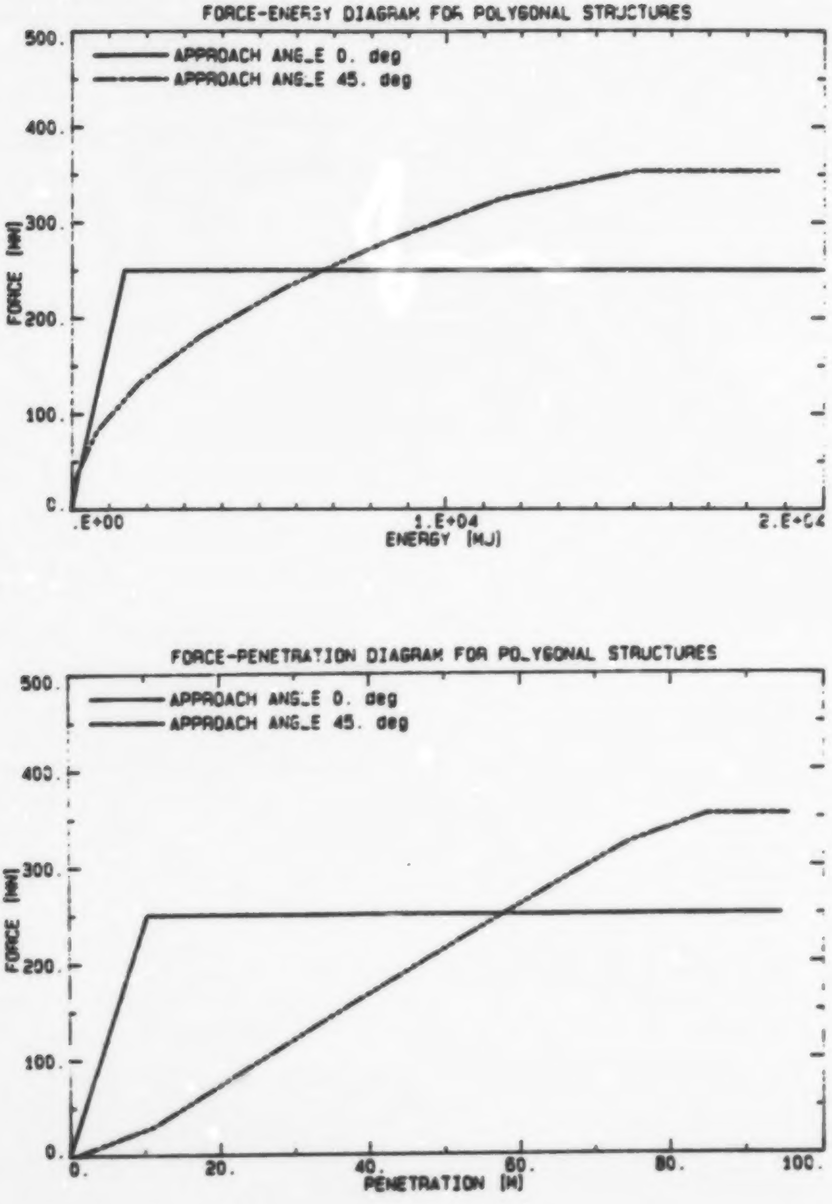


Fig. 4.13. Results of Penetration-Force-Energy Model for Vertical Square Structure (width = 100 m)

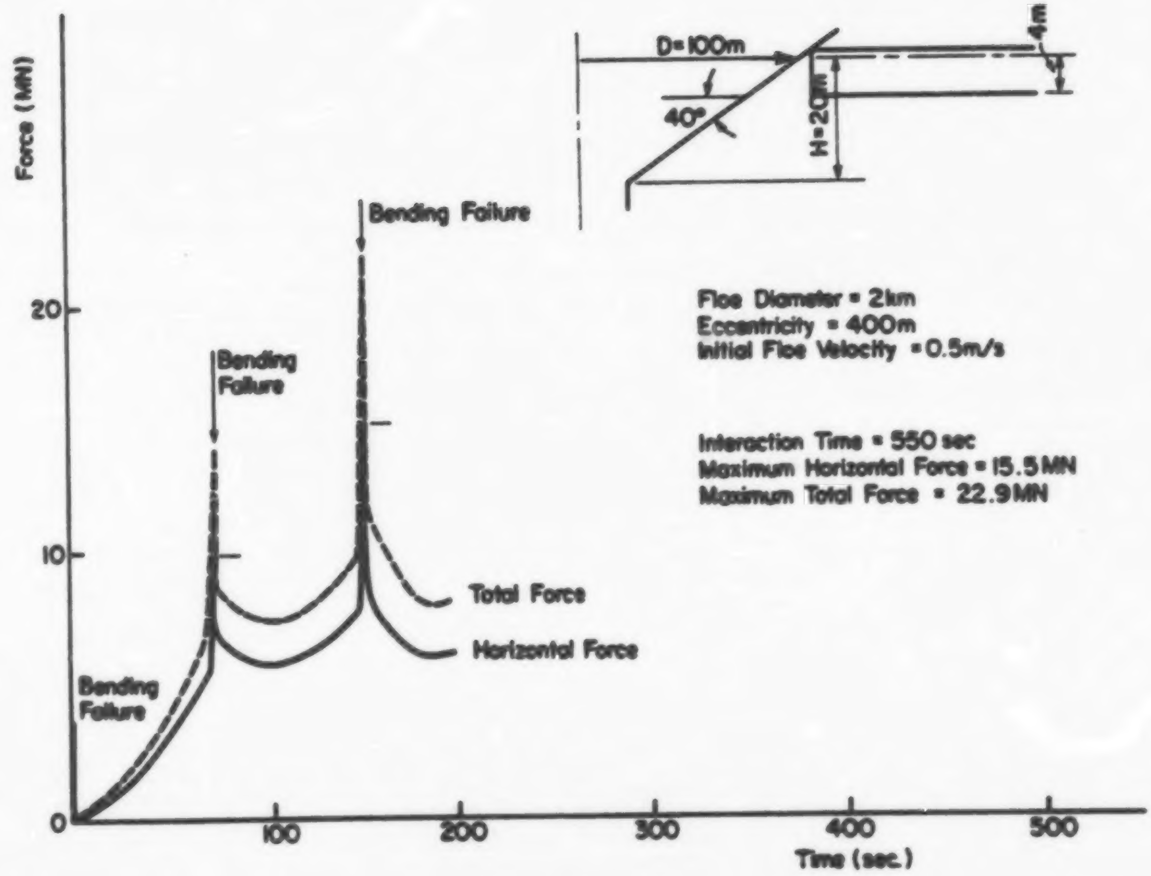


Fig. 4.14. Force History for Multiyear Floe Interaction With a Downward Breaking Cone

structure after the previously broken piece has completely ridden up the structure. The penetration interval between these peaks is equal to the length of the broken ice piece given by Eq. 4.10. It is noted that these peaks occur in a short period of time and thus the energy dissipated during this phase is negligible.

In the present approximate model the ride-up force is calculated from the weight and friction of the ice volume riding up the structure for a given value of the penetration. Force peaks equal to the ice breaking force are superimposed on the ride-up force at intervals equal to the broken ice piece length. This is illustrated in Fig. 4.15 for a floe with the same dimensions as in the previous example in Sec. 4.3.4.1. The ice flexural strength is 0.2 MPa, Poisson's ratio is 0.3 and the modulus of elasticity is 5 GPa. The structure is an upward breaking cone with a waterline diameter of 70 m, freeboard of 20 m and a 60^o angle to horizontal. The horizontal and vertical force components are plotted against the penetration and energy dissipated. The dotted lines give the ride-up component in each case without the superimposed breaking force. Note that on the figures, the maximum force up to a given penetration or energy is given. This is why the plot does not drop back to the ride-up force after each breaking event.

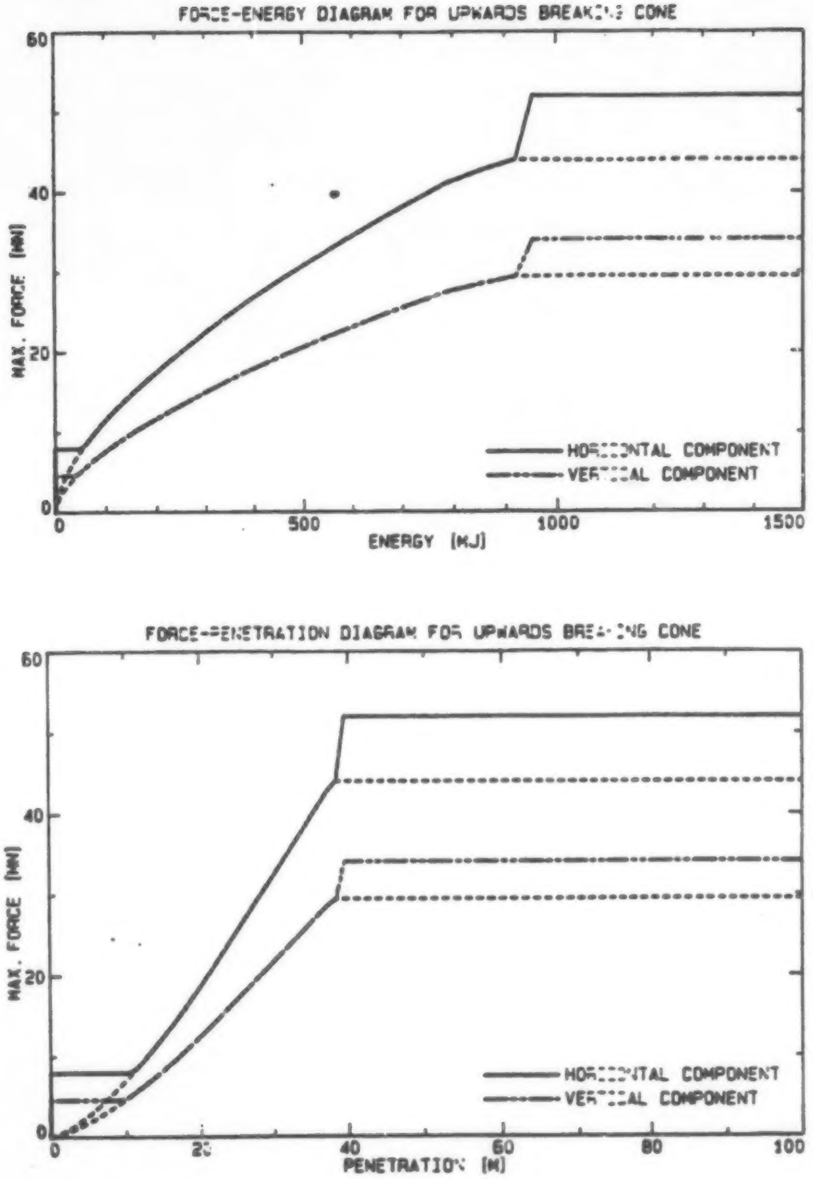


Fig. 4.15. Results of Penetration-Force-Energy Model for Upward Breaking Conical Structure

CHAPTER 5

PROBABILISTIC AND EXTREMAL MODELS FOR ICE LOADS

5.1 General

Stochastic processes model the random variation of a certain quantity of interest in a continuum. They are thus suited for probabilistic modelling of ice forces where the variation of ice load or pressure in time is studied. The stochastic process models such parameters as the magnitude of the ice load at a given point in time and can also be used to estimate the maximum ice load occurring during a given period of time. The latter provides the basis for selecting design ice loads and pressures.

As will be shown in this chapter, the maximum value of a random process depends on two aspects, the severity of the process and the extent of the period during which it applies. The severity describes the magnitude of the load or pressure at any point in time and is determined by such parameters as the ice thickness, velocity and mechanical properties. The extent of time for application of the process defines the "exposure level" of the structure to the loading scenario being considered. This is determined by such factors as the frequency of occurrence of the load scenario and the length of the season during which it applies.

The type and parameters of the stochastic process used in modelling a certain load scenario depend on the characteristics of loading and the values of the associated environmental parameters. In this chapter two basic types of stochastic processes are described, namely the discrete compound poisson process and the continuous time process. The extremal analyses used in calculating the maximum ice load from each type of process are also described. This is followed by an account of the statistical models developed for calculating the parameters that quantify each process, and for combining different processes to obtain the final maximum load or pressure distribution. This chapter describes the main concepts and models which are used in developing the overall probabilistic global and local force models, with relevant illustrations from the ice load problem. The use of these concepts to construct overall models for selecting design criteria is discussed in Chapter 6.

5.2 Stochastic Processes for Ice Loads

5.2.1 The Choice of an Appropriate Stochastic Process

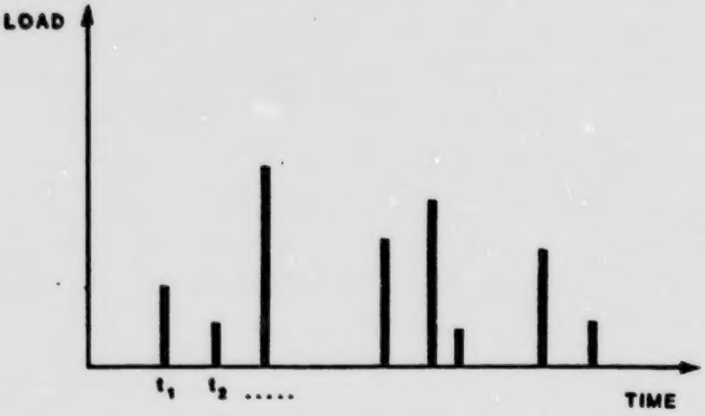
As mentioned in Sec. 5.1, the ice load scenarios described in Sec. 3.5 can be described by one of two types of stochastic processes (see Fig. 5.1):

a) Discrete process: for which the random quantity of interest (i.e. ice load) assumes actual values at localized points in time between which the random quantity has a value of zero. This process can be seen to be suitable for discrete ice loading scenarios such as multiyear floe, iceberg or first year ridge interactions.

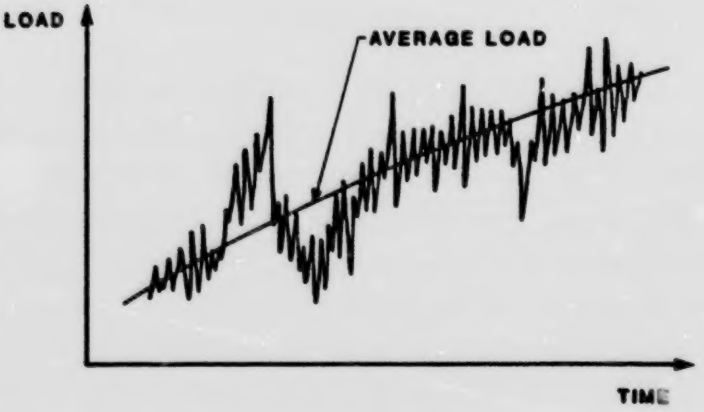
b) Continuous process in which the random quantity of interest (ice load) is continuously defined at any point in time. This is an appropriate model for loading by first year level ice during the full ice cover (winter) season in the pack ice zone. The example in Fig. 5.1b represents this scenario. It is noted that the systematic increase in ice load is due to the growth of the thickness of first year ice during the winter season. This trend would not be observed in the break-up season where the thickness of the ice does not undergo significant changes. In the break-up season, however, the process would be interrupted by periods of open water. Handling such variations of the continuous process will be addressed in Chapter 6.

5.2.2 Discrete Process: The Compound Poisson Process

The Poisson process provides a mathematical model for physical situations characterized by events occurring at random points in a continuum. The process models the probability distribution of the number of events occurring in a given interval of the continuum (in the context of this study, number of interaction in a given period of time). This number is given by:



(a) DISCRETE



(b) CONTINUOUS

Fig. 5.1. Discrete and Continuous Ice Load Processes

$$P_N(n) = \frac{e^{-\lambda t}(\lambda t)^n}{n!}, \qquad n = 0, 1, 2, \ldots \qquad (5.1)$$

where n is the number of events, t is the extent of the interval, and λ is the rate of the process defined as the average number of events per unit interval.

The underlying assumptions of the Poisson process are as follows (Benjamin and Cornell, 1970):

1. Stationarity: The probability of an incident in a short interval of time t to t + h is approximately λh, for any t;
2. Nonmultiplicity: The probability of two or more events in a short interval of time is negligible compared to λh (i.e., it is of smaller order than λh);
3. Independence: The number of incidents in any interval of time is independent of the number in any other (nonoverlapping) interval of time;

all of which are reasonable for discrete ice feature loading scenarios.

The appropriateness of the Poisson process for ice feature arrivals can also be demonstrated by regarding it as a limiting case of the Bernoulli process. In the latter a series of trials are considered with probability of success p in each trial. Consider each ice feature in the area of interest to be a potential impact (i.e. a trial). Depending on the movement patterns, each feature has a probability p of actually hitting the structure (i.e. success). If the number of ice features is m, then the number of successes (impacts) n in m trials can be modelled by a binomial distribution. It can be shown that in the limit, as m increases and p decreases while mp is constant, the process tends to a Poisson process with a value of $\lambda t = mp$.

Although the rate of the process is often introduced as a constant, this is not a necessary assumption for the use of the Poisson model. This is of importance for the present study, since the impact rate changes throughout any given season depending on the ice concentration and speed. The model is valid for varying rates as long as λ represents the average rate of the process.

If the Poisson process is used only for counting the number of occurrence of the event of interest, it is termed the simple Poisson process. A more appropriate type for this study is the compound Poisson process, where an auxiliary random quantity X representing the magnitude of the event (i.e. ice load) is associated with each occurrence. This is represented by the height of each spike in Fig. 5.1(a). Usually the compound Poisson process would quantify the sum of all X_i values in a given period of time. For the present design ice load application one is not interested in the sum but in the maximum value of X. This will be discussed in Sec 5.3 which deals with extremal analysis.

5.2.3 Continuous Processes

A continuous stochastic process is referred to as a stationary process if all its moment functions are unchanged with a shift on the time scale. A simple consequence of this result is that the mean (i.e. the first moment) of the process at any number of arbitrarity selected time values t_1, t_2, ... is equal to the mean of the process at $t_1 + T$, $t_2 + T$, ... where T is an arbitrary time shift. This is a reasonable assumption for partial ice cover (break-up) conditions where the season is usually short and the ice thickness is more or less constant. It is, however, clearly not applicable to the winter case where there is a systematic increase in the average force due to the growth of ice thickness with time (see Sec. 5.2.1).

As will be shown later (see Sec. 5.2.3) the double exponential distribution is a useful tool which will be used in calculating the extremal load probability distribution for continuous processes. The use of this distribution can be justified based on the appropriateness of the assumption that the values sampled from the process are independent and identically distributed. (For more rigorous assumption and derivation of the double exponential distribution for extremes see Cramer and Leadbetter, 1967). For these values to be identically distributed at any point on the time scale, it can be seen that the process needs to be stationary.

In this study the stationary process will be used as a basic model for all continuous ice load scenarios in order to make use of the double exponential distribution for load maxima. A non-stationary process will be idealized by dividing it into smaller intervals within which the process can be reasonably approximated with a stationary process. This will be discussed further in Chapter 6.

5.3 Extremal Models for Ice Loads

5.3.1 General

For design purposes, the engineer is interested in the maximum or extremal load Y occurring in a series of load values $\{X_1, X_2, ..., X_n\}$ generated during the loading process discussed in Sec. 5.1. The probability distribution of the individual load values X_i is called the "parent" distribution and denoted $F_{X_i}(x_i)$. The required tool for selecting design criteria (see Chapter 2) is the probability distribution $f_Y(y)$ where Y is given by:

$$Y = \max \{X_1, X_2, ..., X_n\} \tag{5.2}$$

Let $F_Y(y)$ represent the cumulative probability distribution of Y. $F_Y(y)$ is defined as the probability that Y does not exceed a certain value y. $F_Y(y)$ can be derived from a simple argument. $Y \leq y$ is satisfied if all X values are $\leq y$. Thus:

$$p\,(Y \leq y) = p\,(X_1 \leq y \cap X_2 \leq y \ldots \cap X_n \leq y) \tag{5.3}$$

Assuming that the samples X_i, i = 1, 2, ... n are independent Eq. 5.3 becomes:

$$p\,(Y \leq y) = p\,(X_1 \leq y)\ p\,(X_2 \leq y) \ldots p\,(X_n \quad y) \tag{5.4}$$

If we further assume that the samples X_i, i = 1, 2, ..., n are identically distributed, i.e. taken from the same parent istribution $F_X(x)$, Eq. 5.4 becomes:

$$F_Y(y) = F_X{}^n(y) \tag{5.5}$$

Probability density functions $f_X(x)$ and $f_Y(y)$ corresponding to $F_X(x)$ and $F_Y(y)$ for different values of n are plotted in Fig. 5.2 for an exponential parent-distribution. The figure shows that the distribution shifts toward higher values as n increases. This

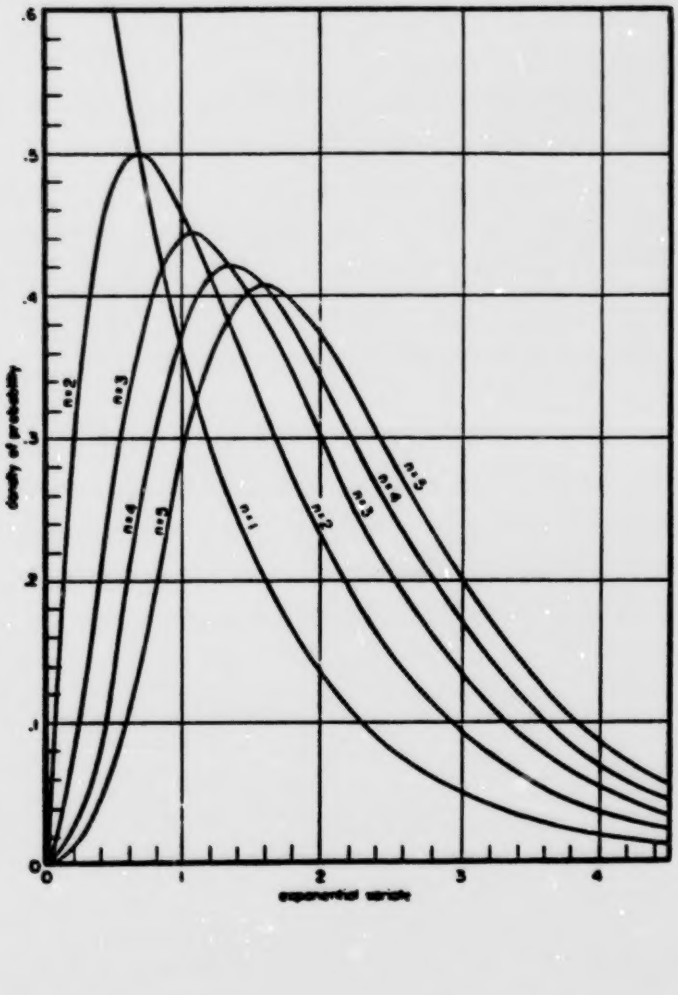


Fig. 5.2 Probability Density Functions of the Largest Exponential Values (Gumble, 1958)
(Horizontal Axis Given in Multiples of Parent Distribution Mean)

means that the load corresponding to a certain probability of exceedance increases as n increases. The extremal load probability distribution can, therefore, be seen to depend on:

1) The shape and parameters of the parent distribution which represents the severity of the interaction or interaction scenario.

2) The frequency of the interaction or more generally, the level of exposure of the structure to a particular scenario.

The estimation of the severity and exposure level for each scenario will be addressed in Secs. 5.4 and 5.5.

5.3.2 The Discrete Poisson Process

In this case the number of interactions N occurring during a period of time t is uncertain and is described by the Poisson distribution given in Eq. 5.1. Given the number of interactions N, the distribution of Y conditional on N, $F_{Y|N}(y,n)$ is as defined in Eq. 5.5. $F_Y(y)$ can be obtained by weighting each $F_{Y|N}(y,n)$ by the probability of N = n and summing for all n as follows:

$$F_Y(y) = \sum_{n=0}^{\infty} F_{Y|N}(y,n) \quad P_N(n) \tag{5.6}$$

Substituting Eqs. 5.1 and 5.5 into 5.6 leads to (Maes, 1986):

$$F_Y(y) = \sum_{n=0}^{\infty} \frac{e^{-\lambda t} (\lambda t)^n}{n!} F_X^n(y) \tag{5.7}$$

Multiplying the numerator by $e^{-\lambda t F_X(y)} \cdot e^{\lambda t F_X(y)} = 1$ we obtain:

$$F_Y(y) = \sum_{n=0}^{\infty} \frac{e^{-\lambda t F_X(y)} \, e^{-\lambda t (1-F_X(y))} \, (\lambda t F_X(y))^n}{n!} \tag{5.8}$$

which simplifies to:

$$F_Y(y) = e^{-\lambda t(1-F_X(y))} \sum_{n=0}^{\infty} \frac{e^{-\lambda t F_X(y)} \quad (\lambda t F_X(y))^n}{n!} \tag{5.9}$$

Now observing that the summation is over another Poisson distribution with rate $\lambda t F_X(y)$, and is therefore equal to 1, Eq. 5.9 simplifies to:

$$F_Y(y) = \exp\left[- \lambda (1 - F_X(y))\right] \tag{5.10}$$

which is a simple and useful result that can be used to calculate the extremal load distribution for a discrete Poisson process given the parent load distribution $F_X(x)$ and the rate of occurrence λt. Note that this result is applicable for any type of distribution $F_X(x)$ including numerical distributions defined by a set of data points, as long as the time process is Poisson.

5.3.3 Continuous Processes: The Asymptotic Extremal Distribution

For continuous processes it is usual to have a time trace of the process on which a large number of X values are recorded (e.g. pressure history). In this case if the X values are considered independent and identically distributed, the double exponential distribution can be used to describe the extreme load $Y = \max \{X_1, X_2, ..., X_n\}$. This result applies for any parent distribution with an exponentially decreasing tail (this includes almost all distributions of practical interest). The double exponential distribution is an asymptotic distribution which applies as $n \rightarrow \infty$ It can, however, be applied for large n values. For a simplified proof of this result see Benjamin and Cornell (1970). The distribution is given by:

$$F_Y(y) = \exp\left[-\exp - \left(\frac{y-a}{b}\right)\right] \tag{5.11}$$

where a and b are distribution constants which are related to the distribution mean and standard deviation by:

$$b = \frac{\sqrt{6}}{\pi} \sigma \tag{5.12}$$

$$a = \mu - \gamma \frac{\sqrt{6}}{\pi} \sigma \qquad (5.13)$$

where γ is Euler constant $\simeq 0.577$ and μ and σ are the mean and standard deviation of the extremal distribution.

It is also worth noting that if there are enough occurrences of X in a period of time to justify the use of the double exponential distribution then if we have m repetitions of the period of time, the new extremal has a double exponential distribution similar to Eq. 5.11 with a new value a' given by:

$$a' = a + b \ln (m) \qquad (5.14)$$

which can be used to calculate the extremal load distribution for a long period of time based on the characterization of the load process during a limited time period, provided that the double exponential distribution applies for the measurement period.

5.3.4 Extremal Distribution for a Normally Distributed Parent

It will be shown in Sec. 5.4 that the normal distribution provides a good model for the sums or averages of random quantities. It is, therefore, suitable for modelling the local ice pressure which is usually defined as the sum of independent random pressure components on subzones of the area considered. The local pressure in this case is a continuous time process. The pressure value at any point in time is normally distributed. For design pressure selection, the probability distribution of the maximum (or peak value) of this process in a given period of time is required.

As discussed in Sec. 5.3.3, the double exponential distribution provides an asymptotic solution for the extreme of most common distributions provided the maximum of a large number of independent values is considered. Assuming that the process is discretized by taking its value at fixed time intervals Δt selected such that independence is satisfied (see Sec. 6.3), and in the case of a normal parent distribution, the parameters of the double exponential extreme are given as follows (Maes, 1985):

$$a = \mu + s \left(\sqrt{2\ell n(k)} - \frac{\ell n\ (\ell nk) + \ell n(4\pi)}{2\sqrt{2\ell n(k)}}\right) \tag{5.16}$$

and,

$$b = s/\sqrt{2\ \ell nk} \tag{5.17}$$

where μ and s are the mean and standard deviation for the normal parent distribution and k is the number of points in the time interval considered T (i.e. $k = T/\Delta t$)

5.3.5 Combining Different Load Scenarios

It is reasonable to assume that ice loads for different scenarios are independent. If different scenarios are denoted 1, 2, ..., n and if the associated extremal distribution are $F_{Y_1}(y_1)$, $F_{Y_2}(y_2$ ..., $F_{Y_n}(y_n)$, then the final extremal can be calculated from:

$$F_Y(y) = \overset{n}{\underset{i=1}{\pi}} F_{Y_i}\ (y_i) \tag{5.18}$$

where π denotes the multiplication of the functions $F_{Y_i}(y_i)$ for all i. The derivation of Eq. 5.18 follows a similar argument to that used in deriving Eq. 5.5.

5.4 The Central Limit Theorem as a Model of Averages

The probability distribution of the average value of a number of random quantities can be derived from the distributions of the individual quantities. This problem arises in the present study in two situations. The first is related to the local ice pressure model where the pressure on a given area is calculated as the average value of pressures on different zones within the design area. This is done to account for the effects of non-simultaneous peaking of the pressure value or different zones (this will be discussed in more detail in Sec. 6.3). The second situation in which the problem of random quantity averages arises is the problem of estimating the probability distribution of the mean value of a certain parameter from data points.

This is needed for modelling the effects of short data records and uncertainty due to lack of knowledge (to be addressed in detail in Sec. 6.4).

The central limit theorem is a very useful tool in this regard. To quote Benjamin and Cornell (1970), the central limit theory states that: "under very general conditions, as the number of variables in the sum becomes large the distribution of the sum of random variables will approach the normal distribution". The theory applies to the mean value since it can be obtained by a linear transformation of sum (i.e. dividing by the number of quantities which are summed). The theory is correct as the number of quantities → ∞, but provides good approximations for limited numbers of values as well. The approximation is better for a certain number of quantities if these are independent and if their distributions are not highly skewed, and it is usually better near the distribution mean than near its tail. Figure 5.3 (Benjamin and Cornell, 1978) shows the distribution of the sums of 2, 3 and 4 uniformly distributed independent random quantities. The subscripts 1, 2, 3 and 4 on the figure denote the number of variables being added. The dotted lines show the approximating normal distributions. The figure shows that the distribution of the sums resembles the normal distribution even for a small number of quantities (i.e. 3 or 4). It is worth noting that if the distributions of the quantities summed are normal, then the distribution of the sum (or average) is normal for any number of quantities in the sum.

Consider a number of independent and identically distributed random quantities $Y_1, Y_2, ..., Y_n$. The central limit theorem implies that the average value of Y can be approximated by a normal distribution with a mean $\bar{Y}$ and standard deviation S given by:

$$\bar{Y} = \mu \tag{5.19}$$

$$S = \frac{\sigma}{\sqrt{n}} \tag{5.20}$$

where μ and σ are the mean and standard deviation of the distribution of Y_i. This is exact if Y_i are normally distributed. Otherwise the approximation becomes better as n increases.

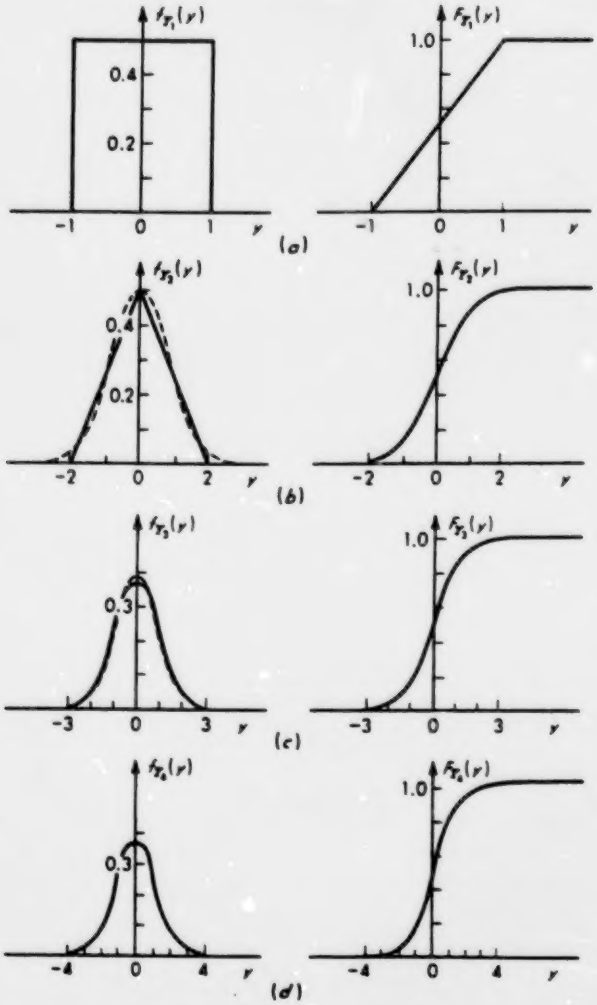


Fig. 5.3 Illustration of the Distribution of the Sums of 2, 3 and 4 Independent Random Quantities with Identical Uniform Distributions

5.5 Models for Exposure to Ice Loading

5.5.1 General

The extremal ice load has been shown to depend on the level of exposure ν which is defined as the product of the time of exposure to a certain scenario t and the average number of events within that time period which could lead to a load maximum λ. For a discrete loading process a loading event is clearly defined as one interaction case. For continuous processes the number of "events" can be taken as the number of possible maxima. Since the maximum can be seen to occur at one of the process peaks, the number of peaks can be used as the number of events.

The above definition of ν assumes that the average rate λ is applicable during the entire period of time t. It is convenient to define t as the length of a certain season during which the scenario is applicable and λ as the rate of occurrence of that scenario. In this case some adjustment of ν may be necessary to account for any limitations on the applicability of the scenario for which t and λ are calculated. This adjustment is in the form:

$$\nu' = \nu \cdot p \qquad (5.21)$$

in which p is the probability that the specifed interaction conditions occur. As an example, consider loading by first year ice in the break-up season. The ice coverage is not complete and there are patches of open water. In this case p is defined as the average probability that the ice is in contact with the structure during the break-up season.

Another example is the case of parameter bounds. In the case of ice island or iceberg interactions the draft of the ice feature that can enter a certain area is limited by the water depth. If the rate of interaction is calculated for all ice features, then it must be multiplied by the probability that the ice feature draft D is less than the water depth D^*. This is given by:

$$p = \int_{0}^{D^*} f_D(d) \quad dd \tag{5.22}$$

More details of such adjustments for different situations arising in the study are given in Chapter 6.

The following two sections deal with the models developed for the estimation of season lengths from season boundaries, and interaction rates of different ice features.

5.5.2 Probabilistic Modelling of Season Lengths

The probability density function of the length of each season (i.e. ice conditions) can be derived from the pdf's of the season boundaries. The following equations can be written:

$$T_j = T_{jk} - T_{ij} \tag{5.23}$$

where T_j is the length of the j^{th} season and T_{ij} and T_{jk} are the boundary dates between the i^{th} and j^{th} and the j^{th} and k^{th} seasons respectively.

In the data analysis in Chapter 3 season boundaries were found to follow a normal distribution. It can be shown that a quantity which is the difference between two independent normally distributed random quantities is also normally distributed with a mean equal to the difference between the means of the two original quantities, and a variance equal to the sum of their variances. Thus:

$$\mu T_i = \mu T_{jk} - \mu T_{ij} \tag{5.24}$$

and

$$\sigma^2 T_i = \sigma^2 T_{jk} + \sigma^2 T_{ij} \tag{5.25}$$

A normally distributed parameter varies between $-\infty$ and ∞. In the case of season lengths, some physical bounds apply. The length of any season, during a one year period for example, cannot be smaller than zero or greater than 365 days. Season lengths are also bounded by the difference between the extreme values of the season boundary dates. This leads to:

$$(T_{jk_{min}} - T_{ij_{max}}) < T_j < (T_{jk_{max}} - T_{ij_{min}}) \tag{5.26}$$

These bounds are applied to the pdf of each season length by truncating the density function at the limiting values, and adding a concentrated probability mass equal to the truncated area at each end of the function.

If the season lengths after applying this truncation are denoted T', the probability distribution of T' is given by:

$$\begin{aligned} p_{T'}(T' = t_{min}) &= \int_0^{t_{min}} N(\mu_T, \sigma_T)\, dt = p_1 \\ f_{T'}(T') &= N(\mu_T, \sigma_T), \qquad t_{min} < t < t_{max}, \\ p_{T'}(T' = t_{max}) &= \int_{t_{max}}^{\infty} N(\mu_T, \sigma_T)\, dt = p_2 \end{aligned} \tag{5.27}$$

where p denotes probability, and t_{min} and t_{max} are the minimum and maximum values of t, and $N(\mu, \sigma)$ is the normal density function for a random quantity, with mean μ and standard deviation σ. The mean value of T' is given by:

$$\mu_{T'} = t_{min} p_1 + \frac{\sigma_T\left(\exp\left\{-\frac{1}{2}\left(\frac{t_{min} - \mu_T}{\sigma_T}\right)^2\right\} - \exp\left\{-\frac{1}{2}\left(\frac{t_{max} - \mu_T}{\sigma_T}\right\}\right)\right.}{2\pi(1 - p_1 - p_2)}$$

$$+ \mu_T(1 - p_1 - p_2) + t_{max}\, p_2 \tag{5.28}$$

The above model was applied to the Prudhoe Bay area considering 3 seasons, open water, full ice cover and partial ice cover. The resulting distributions are shown in Fig. 5.4. The average season lengths are 257, 92, and 20 days for the full cover,

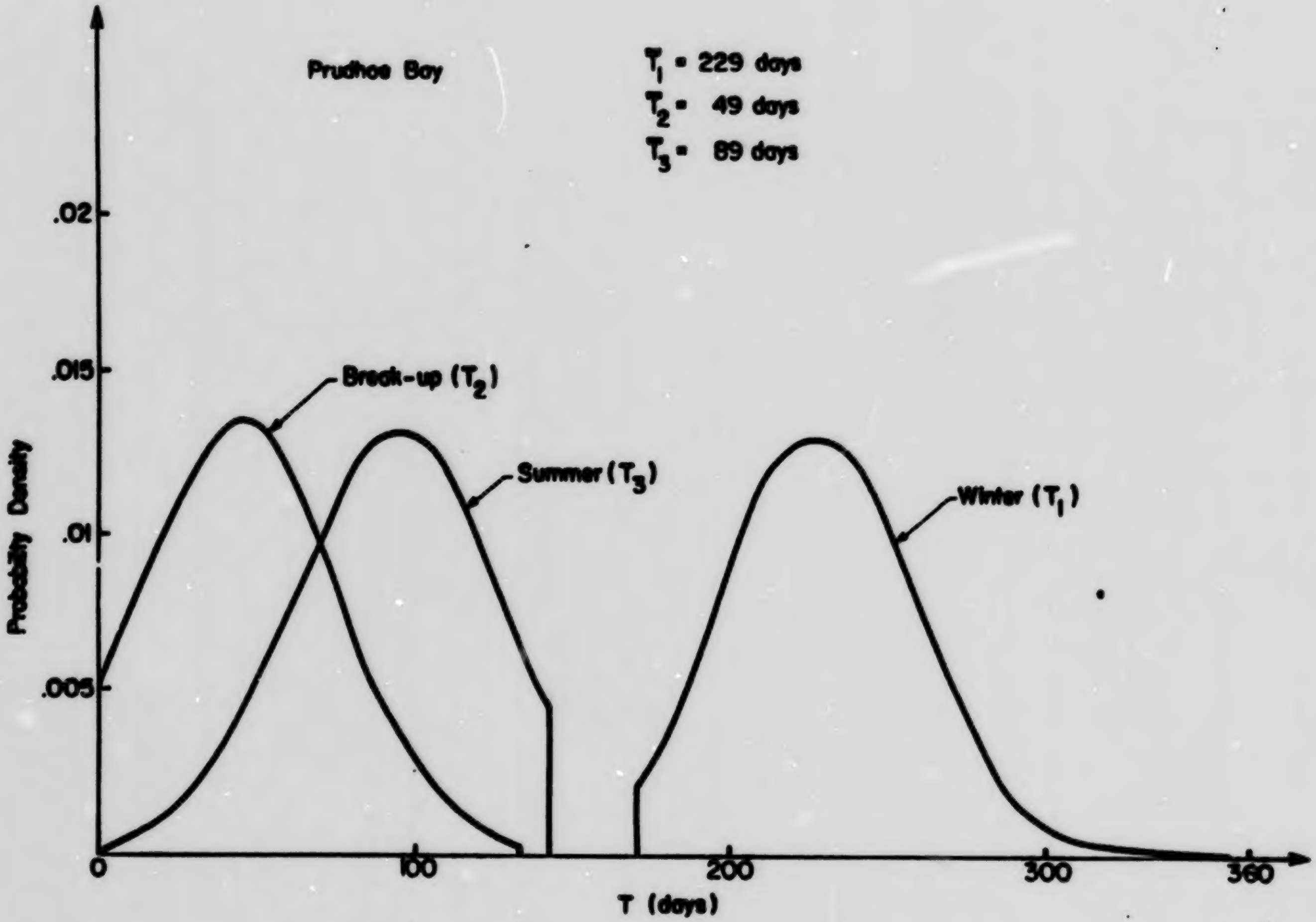


Fig. 5.4. Season Length Probability Density Functions

open water and partial cover seasons, respectively. These add up to 369 days within 1% of the total number of 365 days per year.

5.5.3 Discrete Ice Feature Interaction Rates

5.5.3.1 Areal Features

These include floes, ice islands, ice island fragments and icebergs (see Fig. 5.5a). For a short period of time Δt, we can write:

$$Pr\ (\text{collision}) = \lambda(t)\Delta t = r(b + W_s)\, v\Delta t \tag{5.29}$$

where λ is the interaction rate, r is the ice feature density defined as the number of features per unit area, b is the lateral dimension of the ice feature, W_s is the width of the structure, v is the velocity of the ice feature and t is time. This is based on the interaction probability during a small time period being equal to the ratio of the area swept by moving ice features to the total area. Also from the definition of the ice concentration as the ratio of the sea area covered by ice one can write:

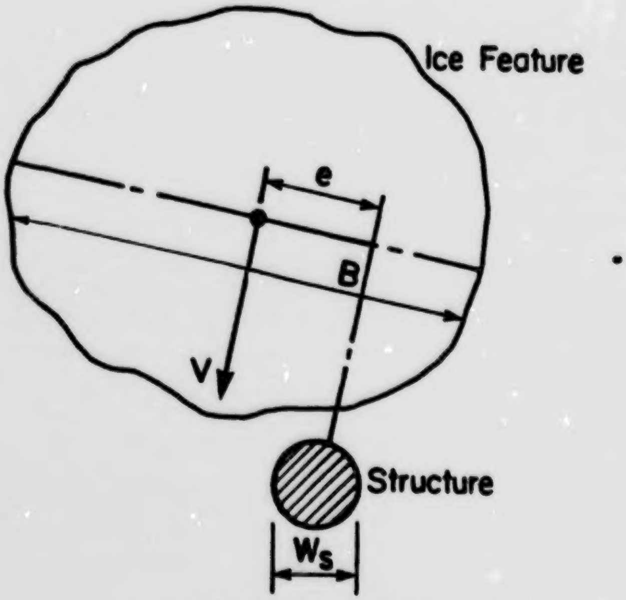
$$c = r \int a\, f_A(a)\, da = r\mu_a \tag{5.30}$$

where c is the ice concentration, a is the feature plan area and μ is the average value. Substituting Eq. 5.30 into 5.29 and integrating over the appropriate parameter density functions gives the average rate of interaction λ as:

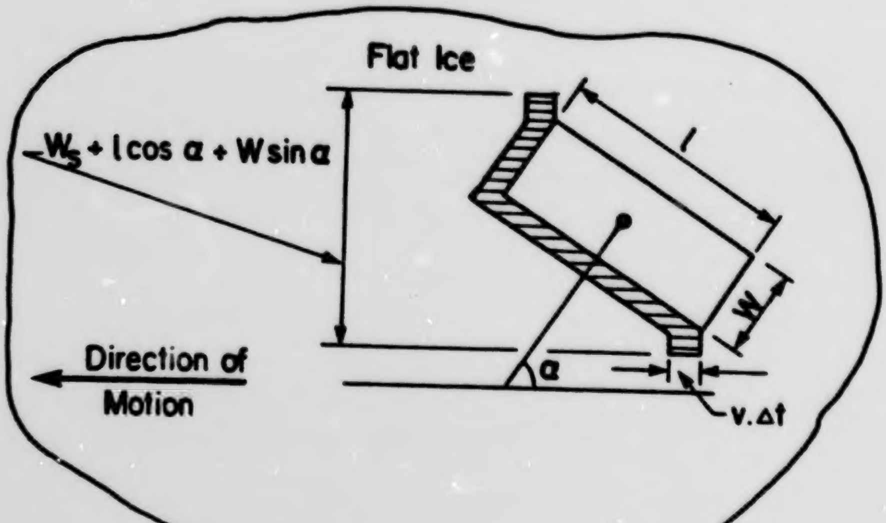
$$\lambda = \iiint \frac{c}{\mu_a} (b + W_s)\, v\, f_{C,V}(c,v)\, f_B(b)\, dc\, db\, dv \tag{5.31}$$

in which we have assumed that B is stochastically independent from both C and V. This leads to:

$$\lambda = \frac{\mu_b + W_s}{\mu_a} \iint cv\, f_{C,V}(c,v)\, dcdv \tag{5.32}$$


Ice Feature
e
B
V
Structure
W_s

(a) Areal Feature


Flat Ice
$W_s + l\cos\alpha + W\sin\alpha$
l
W
α
Direction of Motion
v.Δt

(b) Linear Feature (Ridge)

Fig. 5.5. Illustration of Discrete Ice Feature Impacts

or

$$\lambda = \frac{\mu_b + W_s}{\mu_a} (\mu_c \mu_v + \sigma_{cv}), \tag{5.33}$$

where σ_{cv} is the covariance between C and V. Note that $\sigma_{cv} = \rho_{cv} \sigma_c \sigma_v$, where ρ_{cv} is the correlation coefficient. Consideration of the correlation between C and V accounts for the fact that floe speeds can be reduced for high concentrations due to congestion effects (i.e. ρ_{cv} is negative). Data analysis indicates that ρ_{cv} is approximately -0.25 (Nessim et al, 1986).

The above deviation does not require any assumptions regarding the direction of motion of the ice feature except that the probability distribution is the same for all ice features. This means that the results are equally applicable to directional drift or random movements. The only requirement is that the input parameters should be defined for as large an area as possible around the location of interest, as long as the input parameters are uniform over the area.

Other methods based on ice feature flux can also be used. Flux g is defined as the rate of ice features crossing a certain line in a given time period. If g is available the impact rate would be given by:

$$\lambda = g(\mu_b + W_s) \tag{5.34}$$

where μ_b and W_s are as defined above. Flux methods are suitable for cases where the movement of the ice feature is dominated by a directional drift component.

5.5.3.2 Linear Ice Features

Following a similar argument to that given in Sec. 5.5.3.1 the rate of interaction for a linear ice feature can be calculated (see Fig. 5.5b). Because the development of the result in Eq. (5.33) does not require making any assumptions regarding the direction of ice movement, the methodology is equally applicable to open water ice load scenarios, where separate features move independently, and to closed water cases, where the ice features all move in the same direction with the first-year ice cover. For a linear feature (i.e. a ridge), the width in a direction perpendicular to the direction of motion is given by (see Fig. 5.5b):

$$b = \ell \cos\alpha + w \sin\alpha, \tag{5.35}$$

where ℓ is the feature length, with pdf $f_L(\ell)$, w is its width with $f_W(w)$, and α is its orientation measured from the direction of motion. Assuming the α is uniformly distributed between 0 and Π and that L and W are independent μ_b can be calculated as:

$$\mu_b = \frac{2}{\pi} (\mu_\ell + \mu_w) \tag{5.36}$$

An ice ridge is usually embedded in the surrounding level ice. The rate of interaction is therefore conditional on the presence of level ice. In other words, one is interested in the rate of interaction with a multi-year ridge during (i.e. given) interaction with a multi-year floe. The concentration C in this case represents the percentage of the area on the bottom side of level ice covered with ridges. Consequently, the correlation between C and V discussed in Section 5.5.3.2 for free-floating areal features is not applicable in this case. The average rate can be calculated by substituting μ_b from Eq. 5.36 into 5.33, setting $\sigma_{cv} = 0$ in the latter and substituting $\mu_\ell \cdot \mu_w$ for μ_a. This leads to:

$$\lambda = \frac{2 \mu_c \mu_v}{\pi \mu_\ell \mu_w} (\mu_\ell + \mu_w + W_s) \tag{5.37}$$

5.6 The Severity of Interaction - Calculation of the Parent Distribution

5.6.1 General

The severity of the load or pressure value resulting from a given interaction case with a specific structure is governed by the ice parameters. These include ice pressure, velocity, thickness sizes, eccentricity of impact (if applicable) and so on. The probability distribution of the ice force thus depends on the distributions of input parameters. There are two aspects which need to be modelled in this regard. The first relates to areal ice features and concerns the adjustment of input data to take into account the fact that we are only interested in the properties of ice features that collide with the structure. This piece of information influences one's judgement regarding the size and speed of the features and models accounting for this are described in Sec. 5.6.2. The other aspect is the methodology for the derivation of the load probability distribution from the distributions of the input parameters. In this study a numerical approach based on Monte Carlo simulations is used. This is described in Sec. 5.6.3. There are other approximate methods which are more efficient in terms of the computational effort required. These are based on level II reliability methods (Thoft-Christensen and Baker, 1982) and should be investigated in future studies.

5.6.2 Velocity and Diameter Distributions for Colliding Ice Features

The velocity and diameter probability distributions of a discrete ice feature which collides with a structure are different from those of a randomly selected ice feature (Jordaan, 1983). It can be seen that faster and larger floes travel over a larger water area and are therefore more likely to impact a randomly positioned structure. It follows that those floes which collide with a structure are more likely to be large and fast. The updated distributions can be derived using Bayes' theorem as follows:

$$f_{X|I}(x) = \frac{p(I|x)\ f_X(x)}{\int_{\text{all } x} p(I|x)\ f_X(x)} \qquad (5.38)$$

where X represents the parameter to be updated, I denotes impact and p (•) is the probability of occurrence of (•). From Eq. 5.29 it can be seen that the probability of impact $p(I|\,x)$ is proportional to v and to $(b + W_s)$ where v is the feature velocity, b is the feature width and W_s is the width of the structure. Simple solutions for Eq. 5.38 are available if $f_X(x)$ is gamma or exponential (Jordaan, 1983). The gamma distribution is given by:

$$f_X(x) = \gamma(x|\alpha,\beta) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)}\, x^{\alpha-1}\, e^{-x|\beta} \qquad (5.39)$$

where α and β are the distribution parameters.

In the case of the velocity $p(I|\,v)\, \alpha\, v$• Eq. 38 can thus be written for the velocity v as:

$$f_{V|I}(v) = \frac{v\, f_V(v)}{\int_{\text{all } v} v\, f_V(v)\, dv} \qquad (5.40)$$

Substituting Eq. 5.39 into 5.40 leads to:

$$f_{V|I}(v) = \frac{1}{\beta^{\alpha+1}\,\Gamma(\alpha+1)}\, x^{\alpha}\, e^{-x/\beta} \qquad (5.41)$$

By comparing Eq. 5.41 and Eq. 5.39 it can be seen that the updated distribution of the velocity is a new gamma distribution with parameters $\alpha + 1, \beta$. Figure 5.6 shows the random and updated gamma density functions for multiyear floe velocities in the Beaufort Sea. Note that the updated pdf is shifted toward higher velocity values for the colliding floes.

The result of updating the pdf of the floe width B is slightly different because the probability of impact is proportional to $(b + W_s)$, where W_s is the width of the structure. Taking this into account in the same procedure used for the velocity, the updated pdf is given by:

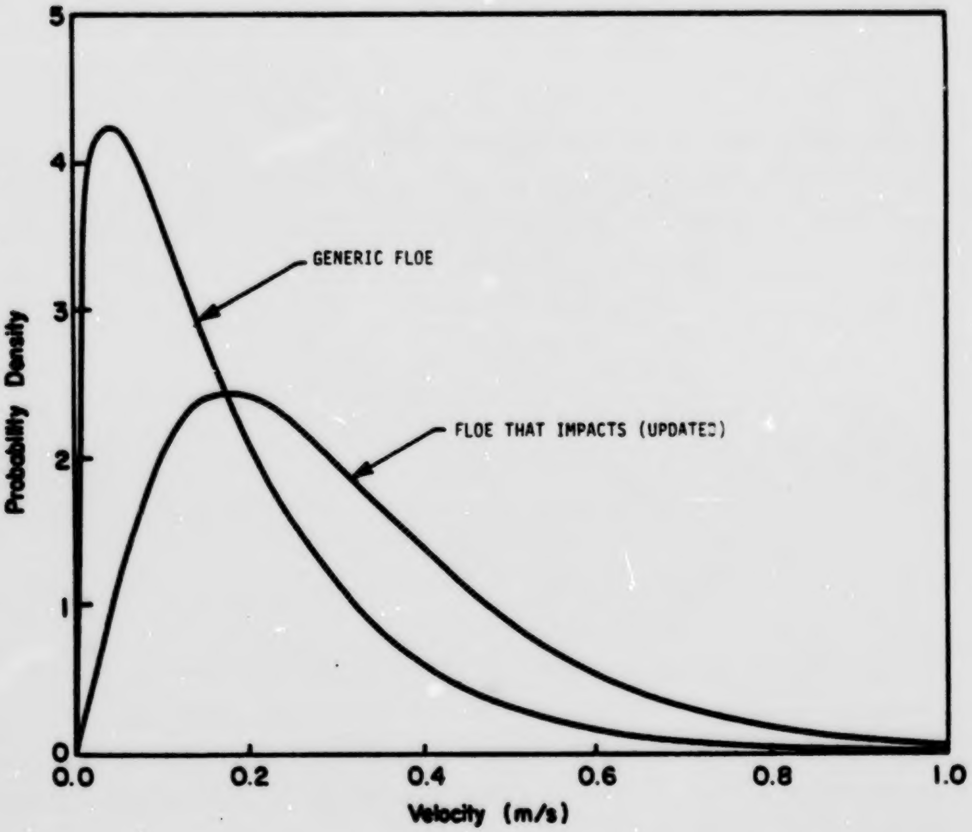


Fig. 5.6 Comparison of the Probability Density Functions for the Velocity of Randomly Selected and Impacting Floes

$$f_{B|I}(b|I) = \frac{(b + W_s)\ f_B(b)}{\int (b + W_s)\ f_B(b)\ d\ b} \tag{5.42}$$

For a gamma distribution of B, $\gamma(b\,|\,\alpha, \beta)$ the final result is given by:

$$f_{B|I}(b|I) = \frac{W_s}{\mu_b + W_s} \cdot \gamma\ (b|\alpha,\beta) + \frac{\mu_b}{\mu_b + W_s} \cdot \gamma\ (b|\alpha{+}1,\beta),\ b \geq 0 \tag{5.43}$$

which is a mixture of the generic gamma pdf and a modified gamma pdf which is obtained by increasing the value of α by unity.

For parameters that are not gamma distributed Eq. 5.38 is solved numerically at discrete points on the distribution function. For the velocity case Eq. 5.40 can be rewritten as:

$$\Delta F_{V|I}(v) = \frac{v}{\mu_v}\ \ \Delta F_V(v) \tag{5.44}$$

Noting that $F_{V|I}(v_{min}) = F_V(v_{min}) = 0$. Eq. 5.44 can be used to calculate $F_{V|I}(v)$ incrementally from $F_V(v)$.

5.6.3 Monte Carlo Simulations

The severity of the interaction is defined by the probability density function (pdf) of the peak load during any interaction event. The derivation of the pdf of the peak load from the probabilistic descriptions of the input parameters and a given ice-structure interaction model is a problem of functions of random quantities. Let X be a random quantity (peak load) defined as:

$$X = g\ \{Z_1,\ Z_2,\ \ldots,\ Z_m\} \tag{5.45}$$

where Z_1, Z_2, ..., Z_m are also random quantities (ice parameters). In principle, the probability density function of X can be calculated from the pdf's of Z_i, i = 1, m, and the function g. The application of this principle was illustrated in Section 5.5.2, where the pdf of the season length was calculated in closed form from the pdf's of the season boundaries. In practice, closed-form solutions are available only for few cases, with special types of pdf's and simple functional forms of g. For the present model the problem is solved numerically using Monte Carlo simulation. The basic principle behind this method is to simulate a number of combinations of the parameters Z_1, Z_2, ..., Z_m from their respective probability distributions. The algorithm used is to generate a basic random number R in the range of 0 to 1 and solve for the value of Z_i which satisfies the condition $F_{Z_i}(z_i) = R$. Each combination can be used to calculate a value of the parameter X until a sufficient number of data points to define $f_X(x)$ is obtained. The number of simulations is determined by limiting the variation in the mean value of X due to an additional data point, to a user-defined tolerance. A smaller tolerance will lead to a larger number of simulated data points. It is noted that this is the only part of the model where Monte Carlo simulation is resorted to as a numerical solution for a problem which cannot be solved in closed form. Due to the computer costs involved, the use of Monte Carlo simulation has been avoided wherever possible, and closed-form solutions have been used in modelling the stochastic process of the occurrence of interaction, calculating the average rate of the process, and evaluating the extremal load pdf.

In order to improve the efficiency of the simulation, the facility for imposing parameter lower bounds is included in the model. In many cases, the extremal load distribution depneds only on the tail of the parent distribution (see Sec. 5.3.). This means that points simulated in the low range of load values do not influence the final solution. By imposing lower bounds on some of the input parameters such as the ice velocity, thickness, or diameter, one would simulate more points on the distribution tail. Thus good solutions can be reached with a fewer number of simulation. In these cases the rate of interaction would be multiplied by the probability that the parameter lies above the specified lower bound. This is done in a manner similar to that discussed in Sec. 5.5.1 Eq.5.22. It is noted that the arbitrary use of parameter lower bounds could lead to distorted results. One must ensure that the part of the distribution tail which influences the extremal distribution is well defined. This depends on the interaction rate and can be determined by the user based on experimentation and comparisons for the particular problem at hand.

CHAPTER 6

INTEGRATED PROBABILISTIC ICE LOAD MODELS

6.1 General

Chapter 5 dealt with the probabilistic models and methodologies which have been developed or selected to deal with different components of the probabilistic estimation of global and local ice loads. In the present chapter the framework which combines those components into integrated models for calculating the loads is addressed. Global forces and local pressures are dealt with in two separate models. These models calculate the probability distribution of the maximum annual load or pressure which is the usual quantity used for defining design criteria for environmental conditions. Each model is illustrated by example results from typical runs.

This chapter also describes statistical techniques which can be used to address the problem of short data records. This is done by separating uncertainty due to lack of knowledge from inherent parameter randomness using distribution parameter estimation techniques. This method is discussed and illustrated with an example in Sec. 6.4.

6.2. Global Force Model

6.2.1 The Overall Model and Load Scenarios

The overall approach is illustrated in Fig. 6.1. It starts by selecting the appropriate ice conditions (seasons) and defining the boundary dates between seasons. These are used to calculate the average season length for each case using the model in Sec. 5.5.2. Within each season the possible loading scenarios are defined (e.g. level ice, multiyear floes or first year ridges). For each scenario, the level of exposure is calculated from the ice parameters as discussed in Sec. 5.5, and the magnitude of the resulting load is also calculated using the models described in Sec. 5.6. Extremal

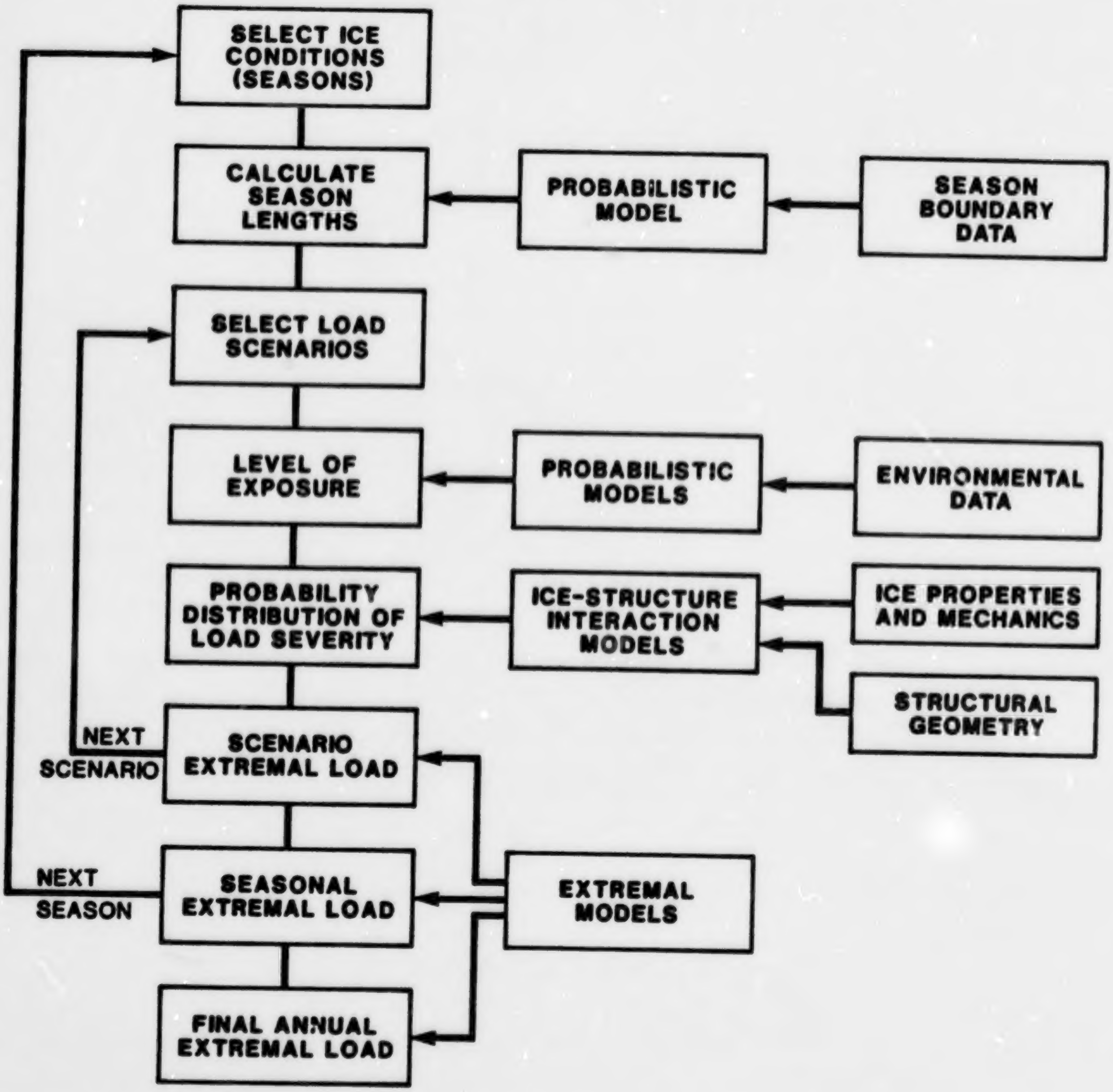

SELECT ICE CONDITIONS (SEASONS)
CALCULATE SEASON LENGTHS
PROBABILISTIC MODEL
SEASON BOUNDARY DATA
SELECT LOAD SCENARIOS
LEVEL OF EXPOSURE
PROBABILISTIC MODELS
ENVIRONMENTAL DATA
PROBABILITY DISTRIBUTION OF LOAD SEVERITY
ICE-STRUCTURE INTERACTION MODELS
ICE PROPERTIES AND MECHANICS
STRUCTURAL GEOMETRY
NEXT SCENARIO
SCENARIO EXTREMAL LOAD
NEXT SEASON
SEASONAL EXTREMAL LOAD
EXTREMAL MODELS
FINAL ANNUAL EXTREMAL LOAD

Fig. 6.1. Overall Approach for Probabilistic Iceload Calculations

analysis (Sec. 5.3) is then used to calculate the probability distribution of the maximum load for each scenario and combine scenarios to calculate the seasonal and annual extremes.

The model is organized in a modular fashion. Each season is dealt with in a separate module and within each season each load scenario is modelled in a separate module as well. These scenario modules call individual ice-structure interaction models and extremal analysis routines. The analysis is activated for a certain season only if required by the user. This is done using a seasons index defined as:

$$I = I_s \times 2^2 + I_w \times 2^1 + I_b \times 2^0 \qquad (6.1)$$

where I_s, I_w and I_b are summer, winter and break-up indexes. These indexes are equal to 1 if the season is considered and zero otherwise. Equation 6.1 results in a unique value of I for any given combination of I_s, I_w and I_b. This index is then used to activate only those seasons which are considered. A similar approach is used for the group of possible scenarios within each season.

The seasons and scenarios considered in the landfast and active ice zones are listed in Table 6.1. For the full ice cover season in the landfast zone only level ice is considered. This is because the movement of ice is very small thus making the probability of interaction with any discrete feature in the ice cover negligible.

6.2.2 Structural Geometries

The structure geometries considered in the model include:

1) Veritcal Circular Structures: These are circular in plan and could be narrow structures such as monopods or wide structures. The structure is characterized by its diameter.

2) Vertical Polygonal Structures: These have a polygonal shape in plan. The structure is defined by the coordinates of its apexes with respect to its centre. The structure must be concave with respect to the origin.

Table 6.1 Ice Load Scenarios

SEASON	LANDFAST ICE ZONE	ACTIVE ICE ZONE
Partial Ice Cover	- first year ridges - level ice - multi-year floes - icebergs - ice islands - ice island fragments	- first year ridges - level ice - multi-year floes - icebergs - ice islands - ice island fragments
Full Ice Cover	- level ice	- first year ridges - level ice - multi-year floes - icebergs - ice islands - ice island fragments
Open Water	- first year floes - multi-year floes - icebergs - ice island fragments - ice islands	- first year floes - multi-year floes - icebergs - ice island fragments - ice islands

3) Cones: The model considers both upward breaking and downward breaking cones. These are characterized by:

- The water line diameter
- The free board for upward breaking cones or the height of the submerged portion of the cone for downward breaking cones.
- The slope angle (positive for upward breaking cones and negative for downward breaking cones)
- The coefficient of friction between the ice and the cone material.

All structures are treated as rigid and fixed. This limitation is due to the types of ice-structure interaction models used, and can be changed by modifying or replacing these modules.

6.2.3 Modelling Discrete Load Scenarios

These include ice floe, ice island, iceberg and first year ridge scenarios in all relevant seasons. The modelling of discrete scenarios is straightforward using the Poisson process of Sec. 5.2.1 and the corresponding extremal model in Sec. 5.3.2.

6.2.4 Modelling Level Ice Movements

The basic tools for modelling level ice scenarios were described in Chapter 5. There are various loading conditions which influence the nature of loading for this scenario. These include the movement speed, the ice zone and the ice conditions (or season). To accommodate these variations further modelling is required in order to formulate different cases in terms of the basic stochastic processes described in Chapter 5. The following subsections will address these different conditions and explain the appropriate models and model combinations in each case.

6.2.4.1 Creep Versus Crushing

As discussed in Sec. 4.2.1 the response of ice depends on the loading speed. Two types of behaviour have been observed:

i) At high speeds the ice crushes, buckles or bends causing the force on the structure to fluctuate randomly. The term "crushing" will be used loosely in the following sections to indicate the above combination of ice failure modes at high speed interactions.

ii) At low speeds ice creeps and the load variation with time is much smoother than in (i) above. Under constant speed the load in this case increases with time up to a steady state maximum load which is reached after a certain period of time.

These two types of behaviour are separated by a cut-off strain rate or speed of movement which will be referred to as the creep-crushing transition speed. The stochastic description of the loading process is different in each case as will be described in Secs. 6.2.4.2 and 6.2.4.3 below. Therefore, for cases where the speed of level ice movement could fluctuate between the creep and crushing ranges, the season length T is divided into two portions as follows:

$$T_{cru} = T\,p_{cru} \tag{6.2}$$

$$T_{cre} = T\,p_{cre} \tag{6.3}$$

where T_{cru} is the crushing time and p_{cru} is the probability of the velocity being above the creep crushing transition speed. Similarly T_{cre} is the creep time and p_{cre} is the probability of the velocity being below the creep-crushing transition speed. It is noted that p_{cru} and p_{cre} add up to 1. The two processes are analyzed separately and then extremal loads are combined using Eq. 5.18.

6.2.4.2 The Basic Creep Model

Uncertainty regarding the load in this case is mostly due to uncertainties in the thickness and speed of movement of the ice. For a given thickness the maximum load occurs at the maximum speed and thus, the variation of speed in time determines the type of process to be used.

A discrete process model is used for creep conditions. The model uses the approaches described in Secs. 5.2.1 and 5.3.2. The discretization of the process is done either at velocity peaks or at regular time intervals. This will be described in the following sections for each specific case.

6.2.4.3 The Basic Crushing Model

This basic process defined in Sec. 5.3.3, is stationary and is defined for a large enough period of time to contain a large number of independent identically distributed measurements. During crushing, fluctuations in ice pressure occur due to variations in the ice properties and response as it crushes along the structure. The pressure at any point in time is defined as (see Fig. 6.2):

$$\sigma = \sigma_m + \sigma_r \tag{6.4}$$

where σ_m is the mean pressure component, and σ_r is a random pressure component. The pdf of σ_r in a given time period is double exponential for which the mean and standard deviation can be assigned on the basis of a pressure time history. Practically, one would obtain pressure-time histories representing similar conditions to the case at hand and defined for a given period of time, say 1 hour. One would then find the highest pressure value during each hour and then calculate the mean and standard deviation of these hourly peaks. The distribution of σ_r can then be defined from Eqs. 5.11 to 5.13 and can also be adjusted for the actual exposure time using Eq. 5.14.

6.2.4.4 The Partial Ice Cover Season

A stochastic ice pressure model for the break-up season is illustrated in Fig. 6.3. The process is assumed to be stationary because the break-up season is usually short (in order of 2 to 3 weeks), making significant changes in ice thickness or pressure unlikely. The loading is interrrupted by periods of open water as can be seen in Fig. 6.3. This is accounted for by adjusting the season length to eliminate open water periods. The ratio of loading time to total season length used is equal to the average ice concentration during the season. This time adjustment reduces the process to the basic model for which the extremal distribution can be obtained as discussed in (a) above.

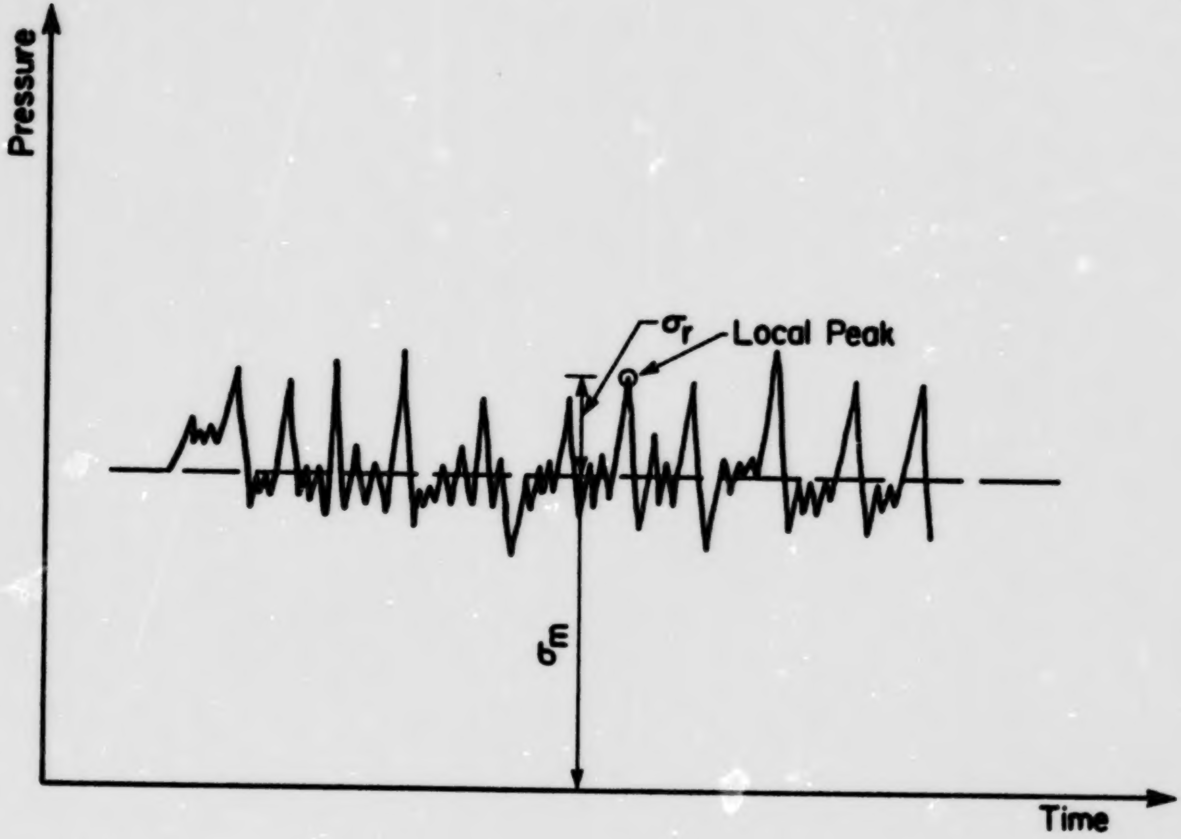

Pressure
Time
σ_r
Local Peak
σ_m

Fig. 6.2 Modelling of the Peak Ice Pressure as the Sum of Mean and Random Components for the Basic Continuous Stochastic Process

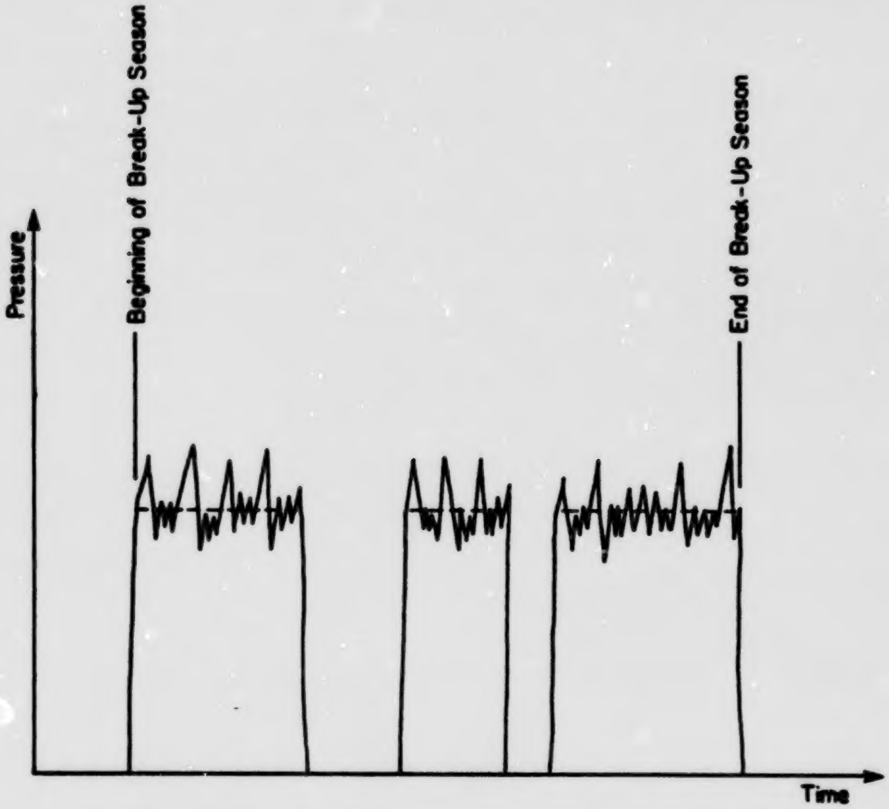

Pressure
Beginning of Break-Up Season
End of Break-Up Season
Time

Fig. 6.3 Illustration of the Stochastic Model for Ice Pressure in the Break-up Season

The loading time is then split into two portions using Eq. 6.2 and Eq. 6.3 for creep and crushing conditions. The values of p_{cru} and p_{cre} are determined from the velocity density function as:

$$p_{cre} = \int_{0}^{V_t} f_V(v)\ dv \tag{6.4}$$

and

$$p_{cru} = \int_{V_t}^{\infty} f_V(v)\ dv = 1 - p_{cre} \tag{6.5}$$

where V is the velocity and V_t is the creep-crushing transition velocity.

Crushing is solved using the basic model in Sec. 6.2.4.3. Creep is discretized at fixed time intervals defined by the user and the average velocity during each time interval is used. The length of these time intervals could be selected as equal to the length of time over which velocities are averaged in the measurements used in defining the velocity distribution.

For conical structures only bending models are used for all speeds. There is thus only one process applicable during all loading. This process is treated in a similar manner to the crushing process with random variations defined for bending strength instead of crushing pressure.

6.2.4.5 The Full Ice Cover Season-Active Ice Zone

In the active ice zones the movement conditions are similar to those for the break-up season. During winter, however, the ice thickness increases systematically and the loading process is therefore non-stationary. This is dealt with by dividing the seasons into smaller time intervals during which the ice can be reasonably assumed to have a constant thickness. One month periods are selected for this study (see Fig. 6.4). Each month is analyzed separately in a manner similar to that used in modelling the break-up season (Sec. 6.2.4.4). The only difference is that no open water

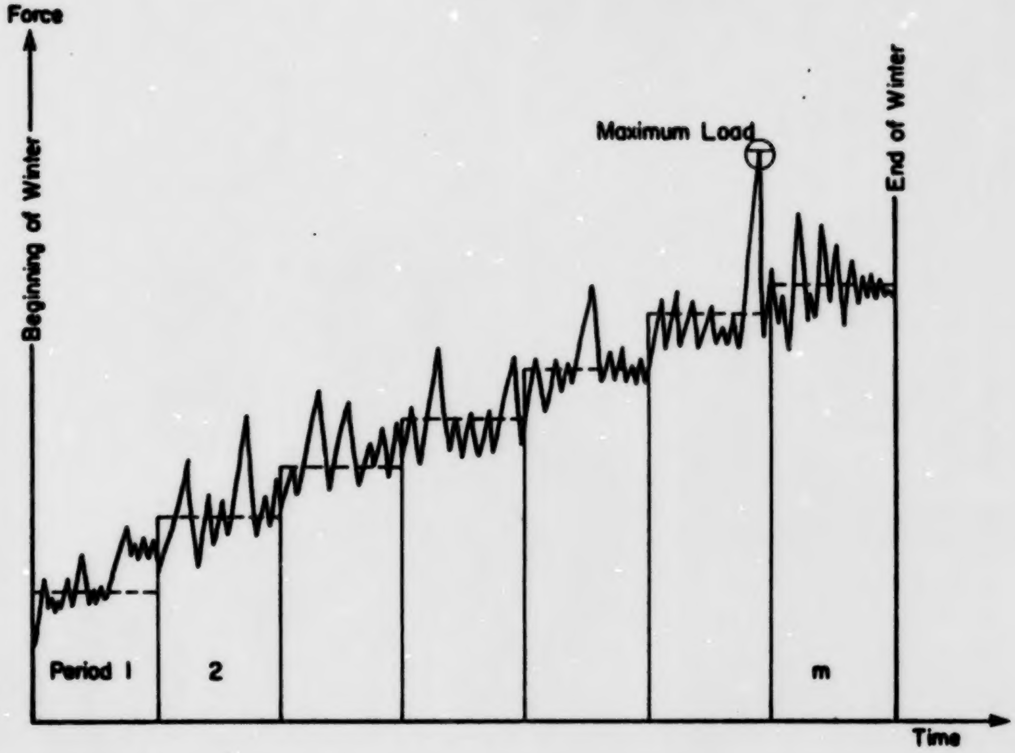

Force
Beginning of Winter
End of Winter
Maximum Load
Period 1
2
m
Time

Fig. 6.4 Schematic of the Discretization of a Non-Stationary Process Into a Series of Stationary Processes

periods exist and therefore no adjustment of the time scale is needed for this factor. The monthly extremes are thus calculated and combined using Eq. 5.18 to obtain the overall seasonal extreme.

6.2.4.6 The Full Ice Cover Season-Landfast Zone

Only vertical-sided structures are considered in the landfast ice zone. The maximum ice movement ratio in the landfast zone in the data set analyzed in the study was about 10 m/hr. For a 100 m wide structure, this corresponds to a nominal strain rate of 5.6×10^{-5}. Average speeds are in the order of 0.4–0.5 m/hr, which would lead to nominal strain rates well below the creep-crushing transition. Creep therefore dominates at normal movement rates. Extraordinary movement conditions, however, have been observed where a large area of ice breaks-off from the landfast ice edge and moves at higher speed during stormy conditions. Crushing conditions are assumed to dominate in these cases. The duration of creep and crushing conditions are calculated from Eqs. 6.2 and 6.3 using:

$$p_{cru} = \frac{n_b \cdot T_b}{T} \tag{6.6}$$

$$p_{cre} = 1 - p_{cru} \tag{6.7}$$

where n_b is the average number of break-off events per season, T_b is the average duration of high speed movement during each event and T is the total season length.

A sample time trace of the ice movement rate in the landfast zone is given in Fig. 6.5 (Spedding, 1977). This is obtained from hourly interrogations of the ice movement, which means that these speeds are averages over a one-hour interval. This is appropriate for the creep model, since the ice speed must be sustained for a reasonable interval of time before the steady state maximum creep load is reached. The load fluctuations can be expected to follow a similar pattern to the velocity fluctuations in Fig. 6.5. The process is therefore discretized at the velocity peaks. The rate of velocity peak occurrence and the magnitude of the velocity at those peaks are required inputs to the analysis. These can be obtained from data records similar to that displayed in Fig. 6.5 and used in the Poisson model described in Secs. 5.2.1 and

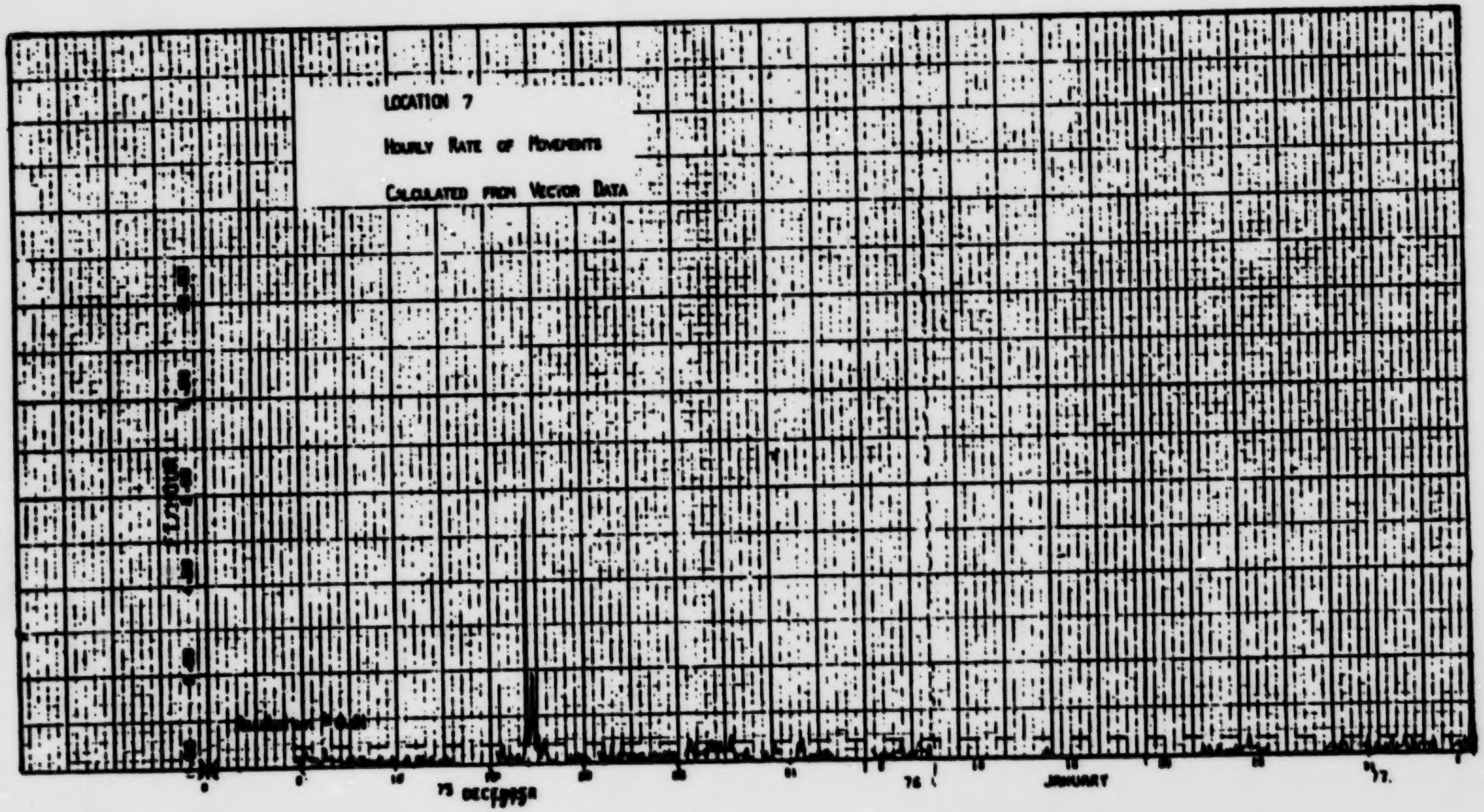


Fig. 6.5 Landfast Ice Movement Pattern (Spedding, 1975)

5.3.2. The crushing process for break-off events is dealt with as described in Sec. 6.2.4.3.

The season is divided into one month periods to account for thickness growth and the model for this is similar to that discussed in Sec. 6.2.4.5 for the active ice zone winter level ice movement.

6.2.5 Summary of Stochastic Models

For quick reference, the stochastic processes used for each load scenario are summarized in Table 6.2.

Table 6.2
Types of Stochastic Processes for Each Ice Load Scenario

Scenario	Ice Conditions	Ice Zone	Movement Speed	Stochastic Process
1. Level Ice	Full Cover	Landfast	Normal	Discrete (at Velocity Peaks)
			Break-off	Continuous
		Pack	Creep range	Discrete (at fixed intervals)
			Crushing range	Continuous
	Partial Cover	All zones	Creep range	Discrete (at fixed intervals)
			Crushing range	Continuous
2. First-Year Ridges	All conditions	Pack	All speeds	Discrete
		Landfast		N/A
3. Areal Ice Feature	All conditions	Pack	All speeds	Discrete
		Landfast		N/A

6.2.6 Environmental Parameters

A default set of input parameters are provided in the model for the Beaufort Sea and Grand Banks areas as described in Chapter 3. Any of these parameters can be changed if better information is (or becomes) available. For discrete ice features, the input probability distributions of the diameter and velocity should be those for a feature selected at random. In the program, these are updated using the model described in Sec. 5.6 before they are used.

There are also some "built-in" parameter distributions which are automatically assigned in the model. These are parameters which are judged to be completely random because there is no reason to believe that any value of the parameter is more likely than another value. These parameters are:

(i) The eccentricity of the collision for a discrete ice feature.

(ii) The ice feature movement direction or approach angle.

(iii) The thickness of first year ice behind a multiyear floe during an interaction in the full ice cover season.

(iv) The percentage of the width of a multiyear floe subjected to first year ice pressure during an interaction in the break-up season.

Distributions for some of these quantities may be updated if more information indicates that they are not uniform.

6.2.7 The Computer Program

The methodology has been incorporated in a computer program which calculates the annual maximum global ice load probability distribution for a given structure and a set of user defined ice parameters. The program can be applied to any Canadian offshore location provided that the required ice data can be entered. The program has the following features:

- Fully interactive input and output.

- A set of built-in default values for environmental parameters which were analyzed based on existing data. The user has the option of modifying any of the given defaults.

- The package is organized in a modular fashion with each element of the problem (e.g. ice-structure interaction models, probabilistic models, extremal models) treated in a separate subroutine. This allows future replacement or modification of different modules with minimal effort.

- Data retrieval and restart facilities are included in the software to minimize computer and operator time losses in case of errors or interruptions.

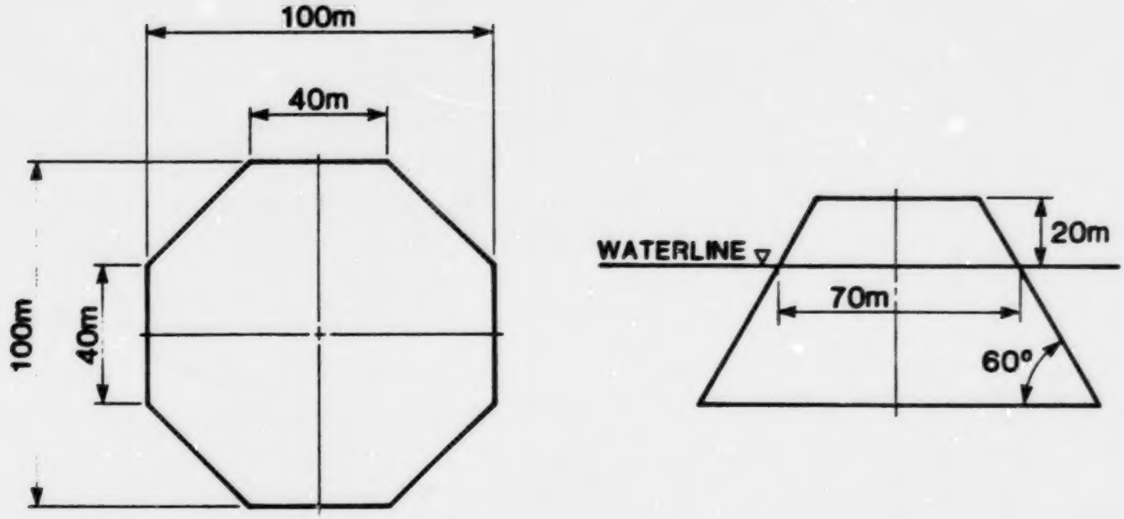
- All data inputs into the program are checked for consistency to avoid problems due to accidental keyboard errors.

- Reasonable bounds are set for all input parameters to ensure the consistency and accuracy of input data. The allowable parameter ranges are wide enough to allow sensitivity analyses.

- The user can select any number of load scenarios to be considered and to develop probabilistic descriptions for any combination of scenarios.

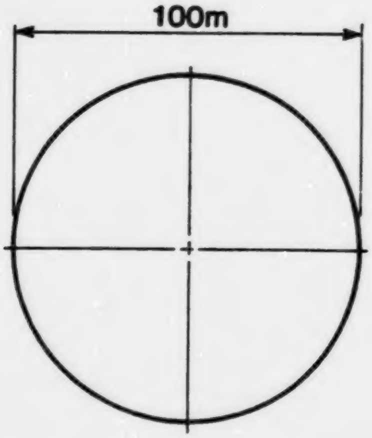
6.2.8 Examples

The structures considered are sketched in Fig. 6.6. The default parameter values listed in Sec. 3.6.2 for the Beaufort Sea and Sec. 3.6.3 for the Grand Banks were used in solving these examples. A lower bound of 2 m was used for first year ridge heights and 500 m for multiyear floe diameters in the Beaufort Sea. These lower bounds result in a better definition of the distribution tail for a given number of simulations, thus resulting in computer time savings.


100m
40m
100m
40m
WATERLINE
20m
70m
60°

1. Polygonal Structure

2. Conical Structure



3. Circular Structure

Fig. 6.6 Structures Used in Sample Cases for Global Ice Load Calculation

6.2.8.1 Example 1. Vertical Polygonal Structure - Beaufort Sea

This structure (see Fig. 6.6) was assumed to be in the Beaufort Sea in the pack ice zone at the edge of the landfast ice (water depth 21 m). In this example all possible scenarios except ice islands and ice island fragments were considered. This includes open water, full ice cover and partial ice cover conditions. Multiyear floes were considered in all three seasons as well as level ice and first year ridges in the full and partial ice cover seasons.

Figures 6.7, 6.8 and 6.9 give sample results for individual scenarios. These results include the load cumulative density functions for one event as well as for the extreme load considering the interaction rate. The following comments are appropriate:

i) The information given for individual scenarios can be used for operational and short-term scenario design decisions. The load distribution for multiyear floes in the summer can be used for example to make decisions regarding construction of systems which may be carried out only in the summer. Also, the extremal loads for individual months in the winter season for level ice can be used to make decisions on the length of the operational season. Note that the extremal load for first year ice increases as the winter progresses due to the growth of ice thickness.

ii) The figures illustrate the dependence of the extremal distribution on the tail of the parent distribution. This is clear from the fact that the extremal distribution coincides with the x axis for some distance before it starts to rise and this initial part does not contribute to the definition of the distribution. This becomes more apparent as the rate of the interaction increases. This is illustrated by comparing Fig. 6.7 which represents a multiyear floe collision rate of 17 per season to Fig. 6.9 which represents a first year ridge interaction rate of 110 per season.

Figures 6.10 and 6.11 show the cumulative density functions and return period relationships for seasonal extremes (considering all scenarios within each season),

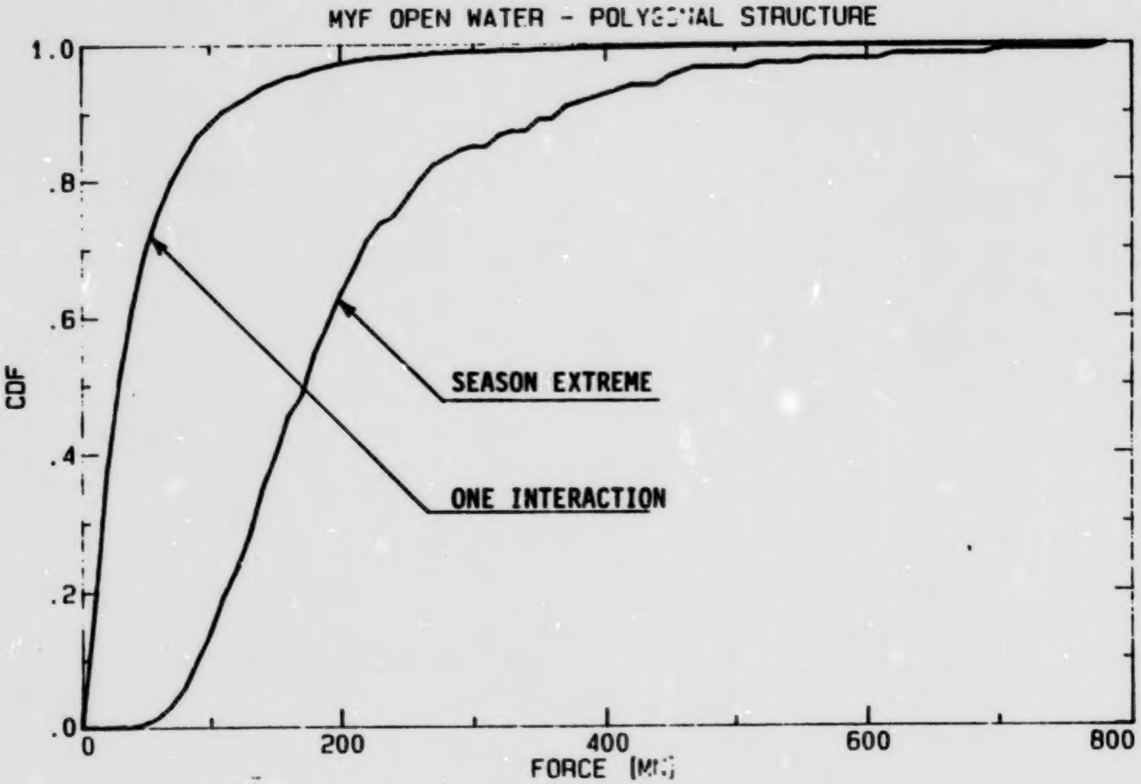


Fig. 6.7 Load Distributions for Open Water Multiyear Floes (Example 1)

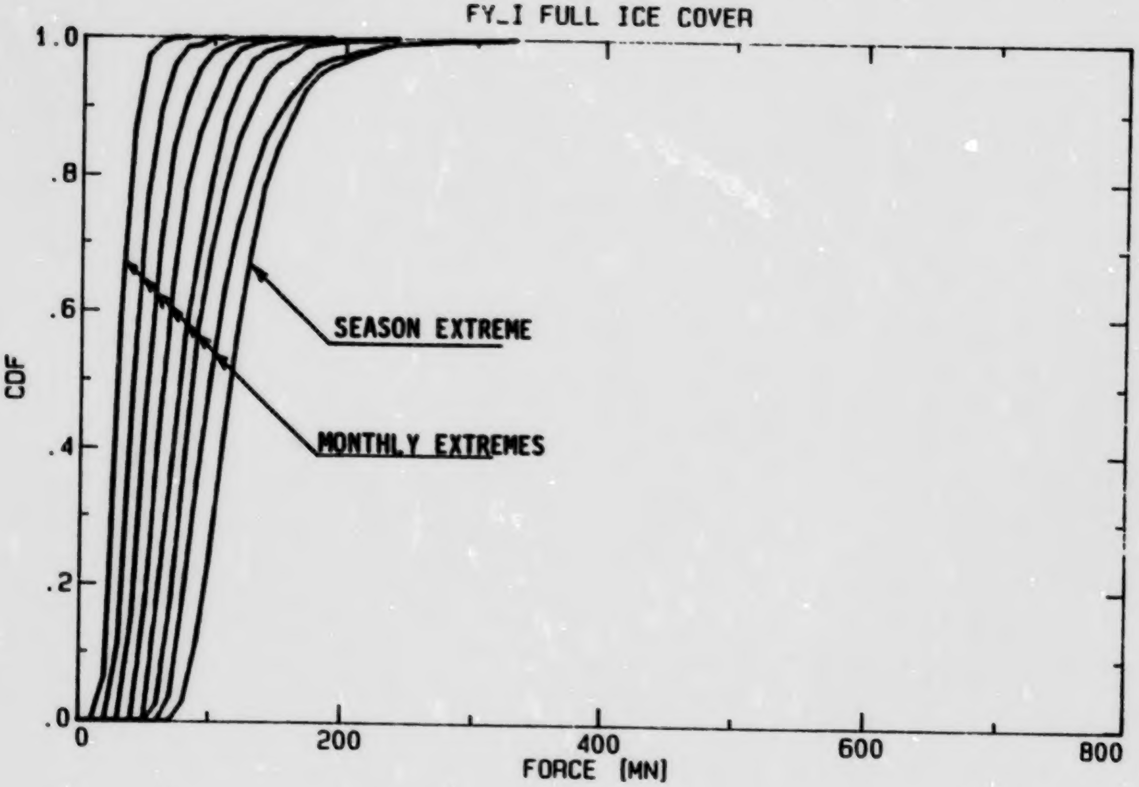


Fig. 6.8. Load Distributions for Full Ice Cover Level Ice (Example 1)

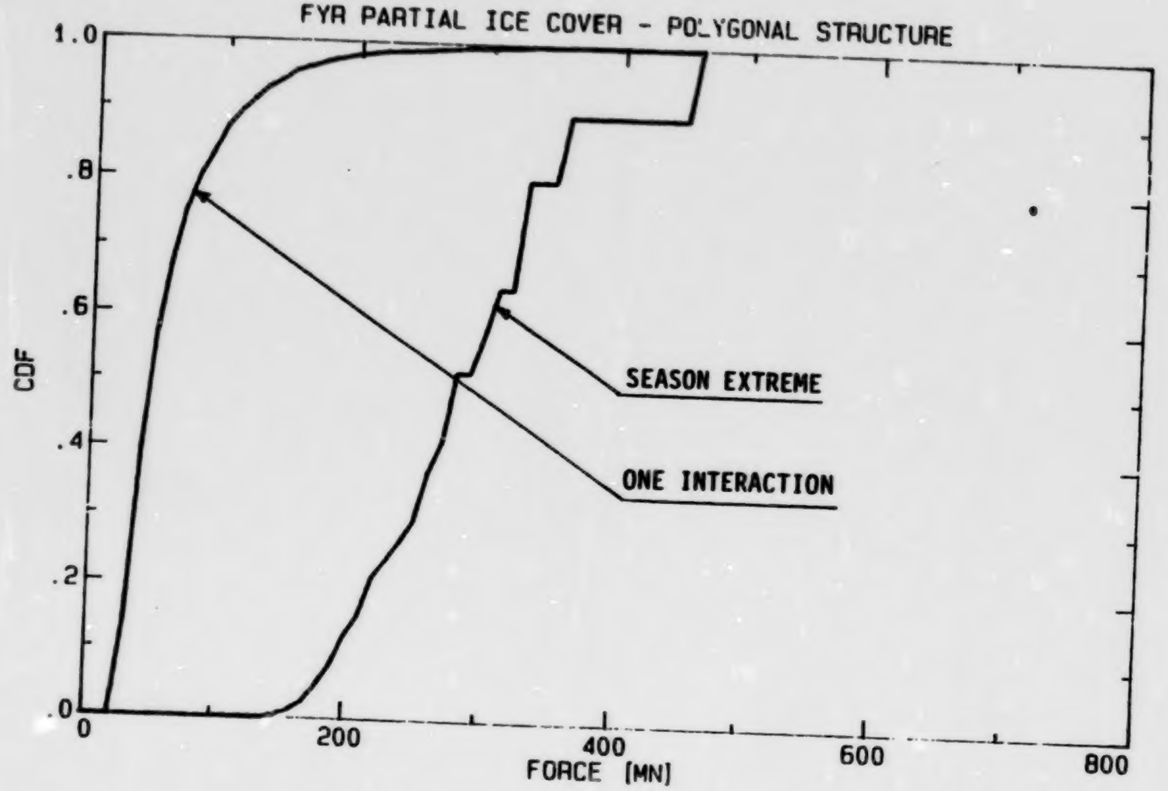
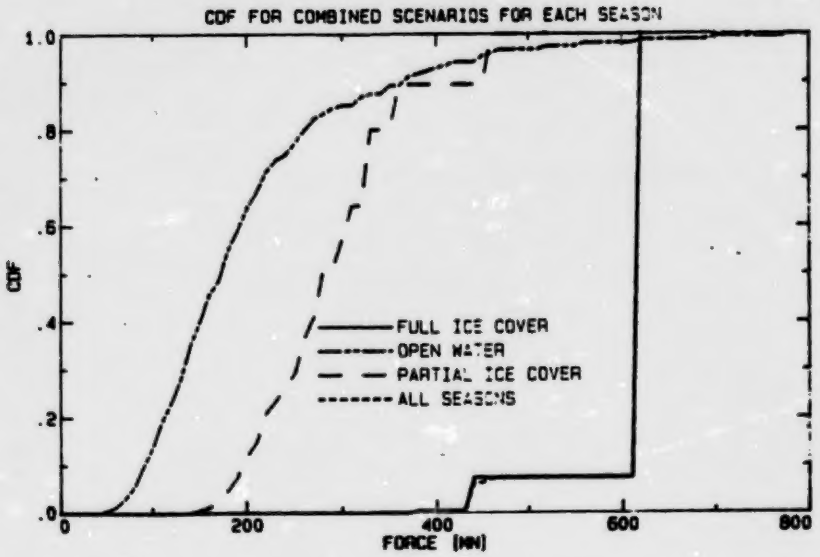
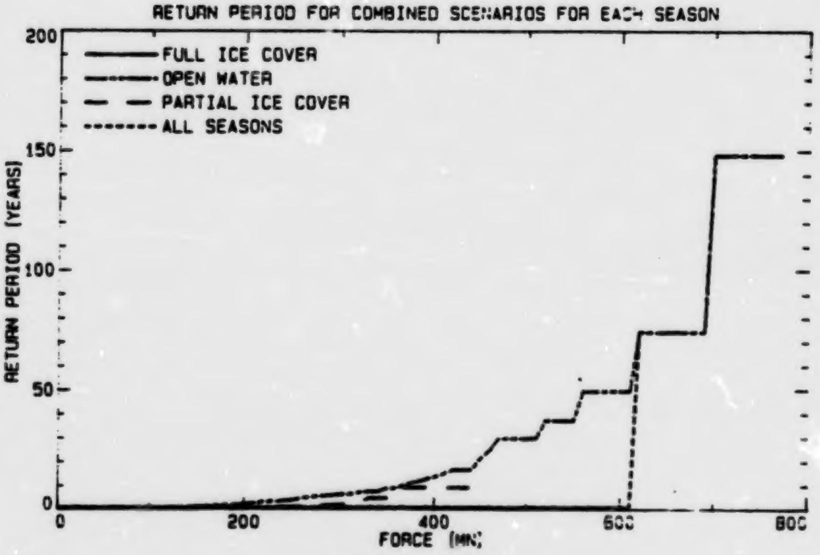


Fig. 6.9 Load Distributions for Partial Ice Cover First Year Ridges (Example 1)

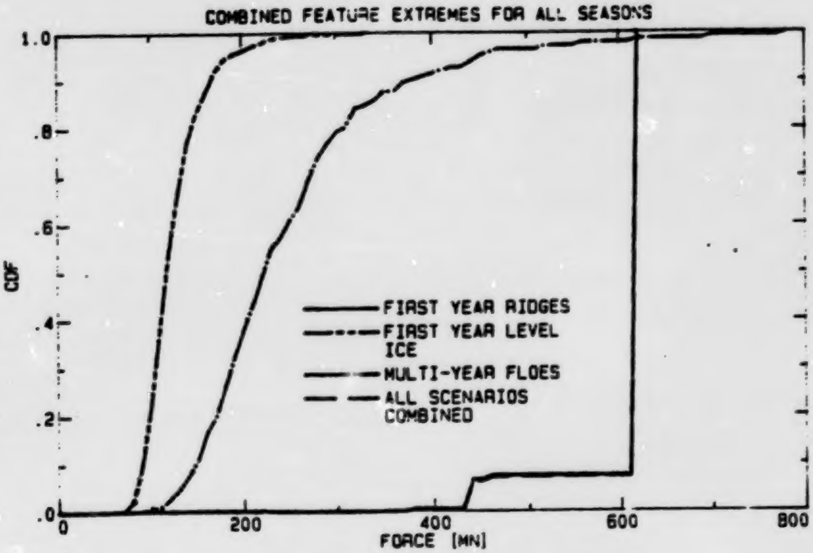


(a) Cumulative Density Format

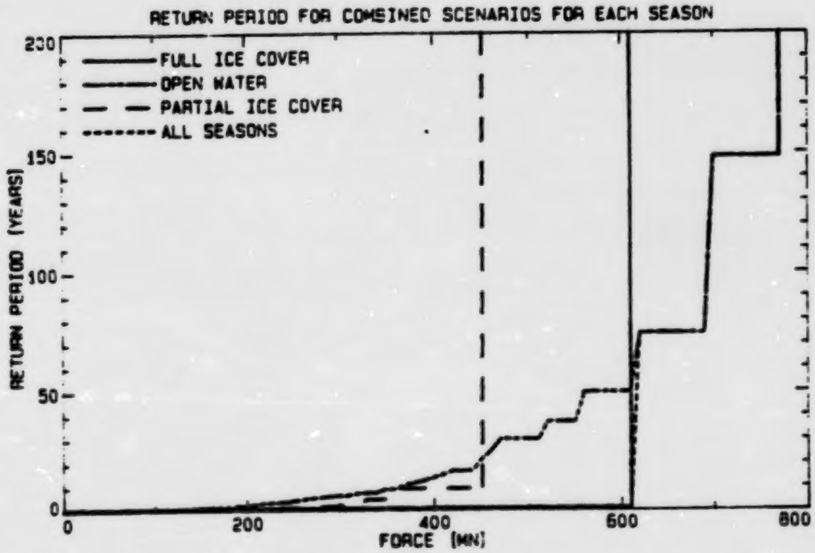


(b) Return Period Format

Fig. 6.10 Load Distributions for Seasonal Extremes and Annual Extreme (Example 1)



(a) Cumulative Density Format



(b) Return Period Format

Fig. 6.11 Load Distributions for Scenario Extremes and Annual Extreme (Example 1)

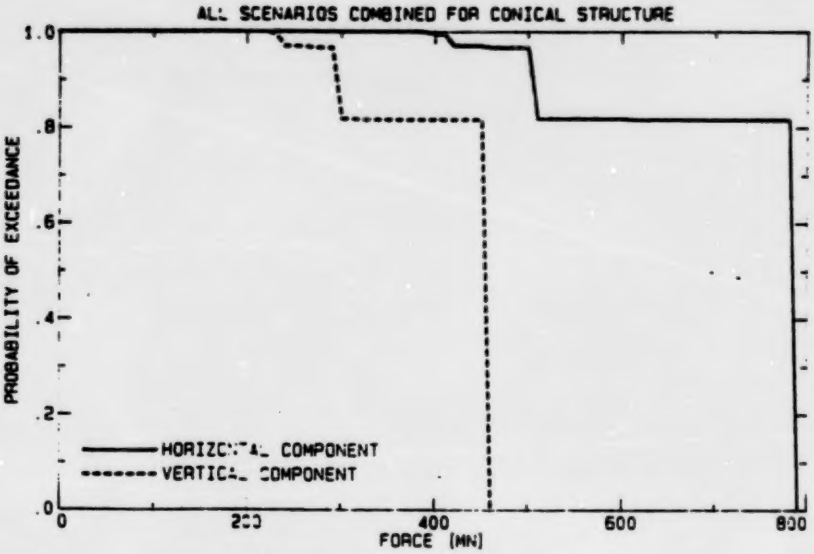
scenarios extremes (considering each scenario for all seasons), as well as the final annual extremal load. It is noted that the plotted curves can be made smoother by increasing the number of simulations.

6.2.8.2 Example 2. Conical Structure - The Beaufort Sea

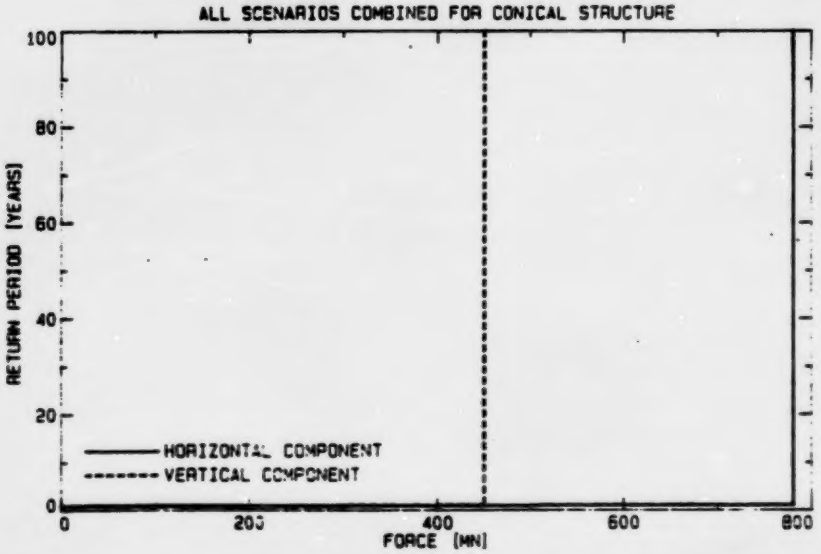
The structure considered is as shown in Fig. 6.6 (Case 2). This was located in the same water depth as in Example 1 (pack ice zone at water depth of 21 m). In this case only the annual extremal load distributions for all scenarios are plotted (Fig. 6.12). Note that the vertical and horizontal forces on the cone are given separately.

6.2.8.3 Example 3. Vertical Circular Structure - The Grand Banks

This structure was assumed to have a 100 m diameter and was placed in the Grand Banks area at water depth of 90 (Fig. 6.6). Open water conditions were assumed to apply year-round, and only iceberg collisions were considered. The results are shown in Fig. 6.13 in the cumulative density and return period formats. It is noted that the loads resulting from icebergs can be very large. The extremal distribution does not begin at the origin but at a point on the CDF axis. This is a reflection of the fact that the rate of interaction is small. The CDF coordinate at zero force (89%) represents the probability that this scenario will not occur during one year.

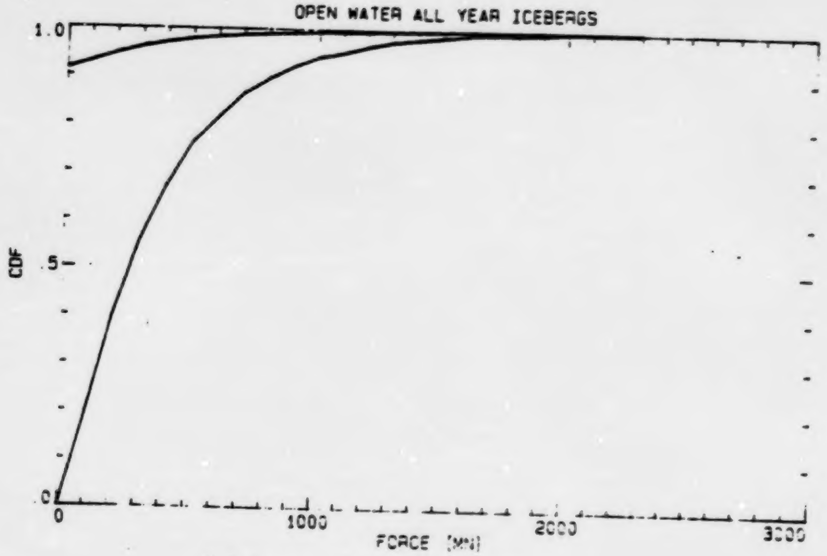


(a) Probability of Exceedance

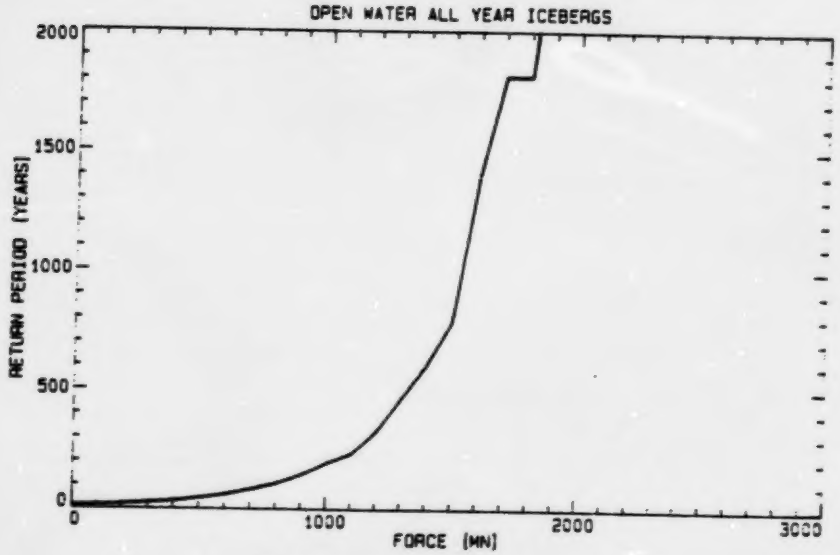


(b) Return Period Format

Fig. 6.12 Annual Extremal Loads for all Scenarios Combined (Example 2)



(a) Cumulative Density Format



(b) Return Period Format

Fig. 6.13 Load Probability Distributions for Grand Banks Icebergs (Example 3)

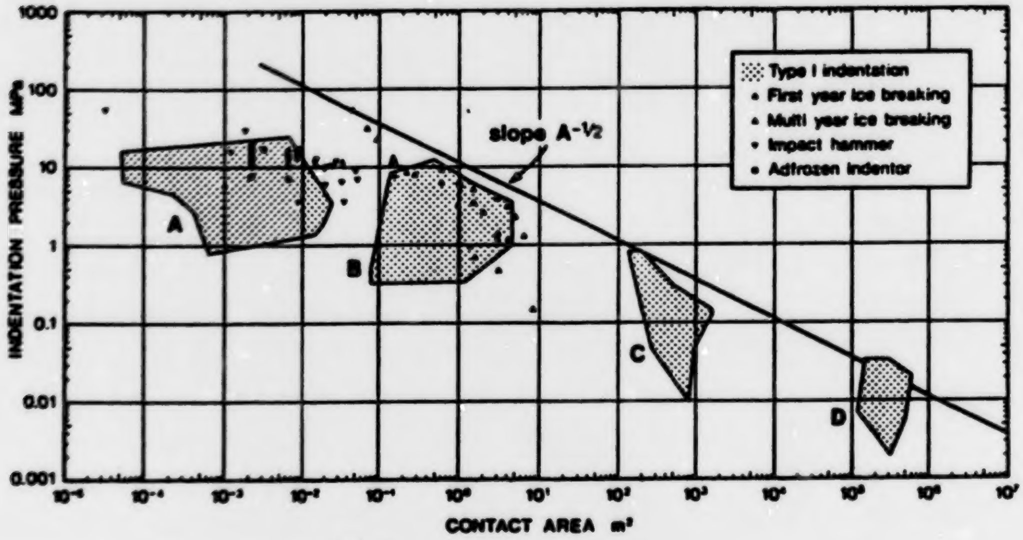
6.3 Local Pressure Model

6.3.1 General

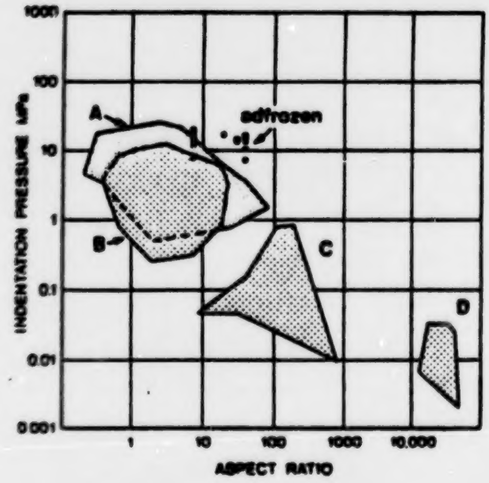
Local pressures on small areas can be substantially higher than pressures averaged over the whole ice structure contact area, and should therefore be assessed separately for local design considerations. The maximum local pressure is influenced by several factors some of which are mechanical and some stochastic. The mechanical aspects of the problem include the ice properties such as temperature, crystalline structure and salinity, the level of confinement determined by the ice geometry and the size effects. On the other hand, probabilistic aspects include the non-simultaneous failure of different zones of the ice-structure contact area, and the fluctuation of pressure with time on a given zone. It is worth noting that time fluctuations can also be explained by a mechanical model of ice failure based on a sequence of pulverization of intact ice and squeezing out of the pulverized ice (Jordaan et al, 1988).

Previous studies have considered the maximum pressure values from different test results and produced suggested design pressures as a function of the loaded area or the aspect ratio (Iyer, 1983 and Sanderson, 1986). An example is given in Fig. 6.14. A curve obtained in this manner includes implicitly, some of the stochastic effects embodied in the process since the peak pressures are plotted and analyzed. The approach, however, is not a rigorous representation of these stochastic effects since these peaks are not based on any specific exposure time, but are likely to correspond to different time periods. Consequently, there is no mechanism to consider the effects of exposure on the extremal load. On the other hand, it is not possible to attach any probabilistic estimate to the recorded pressure values. Naturally, if such an empirical approach is based on a large amount of data representing a time period longer than the expected exposure time, and if an upper bound envelop of the data is considered, then conservative estimates would result.

In the present study, we concentrate on probabilistic aspects. We base the analysis on two assumptions:



(a) Pressure Versus Area



A: Laboratory tests

B: Medium-scale in situ tests, lighthouses and bridge piers

C: Full-scale Arctic islands and structures

D: Meso-scale models.

(b) Pressure Versus Aspect Ratio

Fig. 6.14 Maximum Pressures Measured in Different Tests
(Sanderson, 1986)

i) The pressure time history for any given zone with specified dimensions is a stationary stochastic process.

ii) A large contact area can be subdivided into smaller zones on which the ice deformation process is independent from zone to zone. It is assumed that the size and geometry of these zones is not arbitrary but is a physical property of the ice and interaction coniditions. It is also assumed that pressure history data on one zone is available for a sufficiently long period of time to allow the characterization of the mean and standard deviation of the ice pressure at any point in time. The independent zones are defined by the area a_0 in the case of large ice masses such as icebergs. For ice sheets these zones are defined by their width as a multiple of the ice sheet thickness (i.e. each zone has a depth t and width nt, where n is a physical property). Data required to obtain the information mentioned in this section for large scale field interactions are currently being analyzed in a separate study (GEOTECH, 1988).

Based on the above assumptions, the following two sections will describe a model for calculating the probability distribution of the average pressure on a given area of the structure.

6.3.2 Contact Time Model

The relevance of exposure time to extremal analysis was discussed in Sec. 5.3. Here, a model is given for estimating the expected time during which a certain panel of a structure is in contact with ice of a given type. Assume that the design panel is rectangular in shape with width b^*, depth a^* and is located at a distance y^* above the sea bottom (see Fig. 6.15). In the vertical direction the panel would be in contact with the ice if:

$$\left(y^* + \frac{a^*}{2} - \frac{d}{2}\right) < y > \left(y^* - \frac{a^*}{2} + \frac{d}{2}\right),$$

where y is the height of the ice centreline from the seabottom and d is the ice

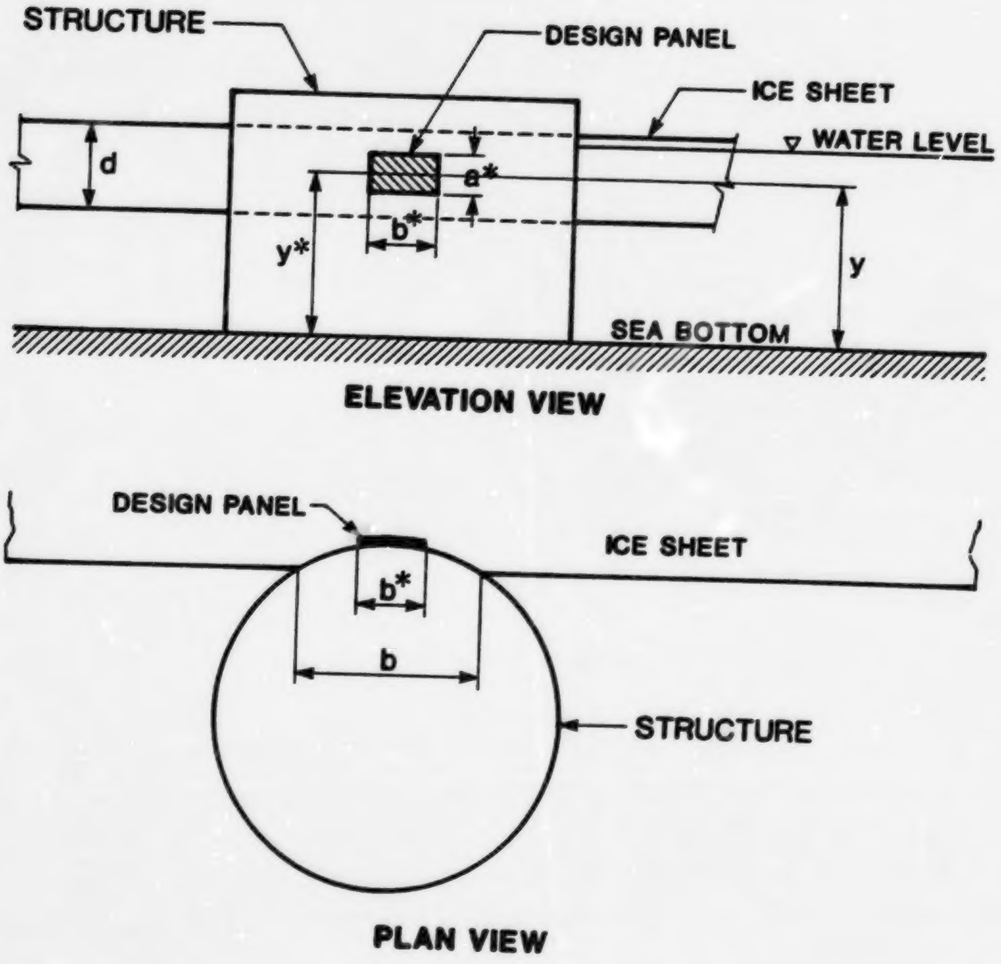

STRUCTURE
DESIGN PANEL
ICE SHEET
WATER LEVEL
d
a*
b*
y*
y
SEA BOTTOM
ELEVATION VIEW
DESIGN PANEL
ICE SHEET
b*
b
STRUCTURE
PLAN VIEW

Fig. 6.15 Geometry of Local Design Area

thickness (y could vary with tide and wave surge). The probability of this occurring p_v is given by:

$$p_v = \int_0^\infty f_D(d) \int_{y^* + \frac{a^*}{2} - \frac{d}{2}}^{y^* - \frac{a^*}{2} + \frac{d}{2}} f_Y(y)\, dy \quad dd \tag{6.8}$$

in which Y and D are assumed independent.

In the horizontal direction, contact occurs if i) b> b*, and ii) if the contact direction and location is such that b* is contained within b. Assuming that contact is equally likely to occur on any point on the perimeter of the structure, the probability of ii) above for a given value of b is $\frac{2b-b^*}{\ell}$ where ℓ is the perimeter of the structure.

The probability of contact in the horizontal direction p_h is therefore:

$$p_h = \int_{\text{all } b} \frac{2b - b^*}{\ell} f_B(b)\, db \tag{6.9}$$

The probability that the design panel will be completely covered by ice is given by:

$$p_c = p_v \cdot p_h \tag{6.10}$$

It is noted that p_c includes the probability of occurrence of contact areas larger than the area of the design panel. The total time of exposure is then given by:

$$T_t = n \,.\, T \,.\, p_c \tag{6.11}$$

Where n is the number of occurrences of the scenario considered and T is the average contact time during that scenario.

6.3.3 Non-Simultaneous Failure Model

This idea was initially proposed by Kry (1978). The non-simultaneous failure of ice on adjacent zones implies that when the pressure is at a peak value on one zone, it may be at a value lower than the peak for another zone. The result is that when pressures are averaged at any point in time for two zones, the peak pressure on the two zones combined is likely to be less than that for one zone (see Fig. 6.16). Thus, σ_r of the averaged pressure decreases as the number of independent failure zones increases. For a given contact area A_c (larger than the design area), the number of zones n can be calculated from:

$$n = \frac{A_c}{A_0} \tag{6.12}$$

where A_0 is the area of each independent zone. For ice sheets A_0 may be better defined as a multiple of the ice thickness, which implies that the independent zones are characterized by a constant aspect ratio r_0 rather than a constant area. In that case the area of one zone for an ice sheet with thickness d is given by:

$$A_0 = r_0 t^2 \tag{6.13}$$

For n zones, the random pressure component σ_{r_n} can be calculated from that for one zone σ_{r_0} as:

$$\sigma_{r_n} = \frac{1}{n} \sum_{i=1}^{n} \sigma_{r_0} \tag{6.14}$$

The distribution of σ_{r_n} can be calculated from Eq. 6.14 and the distribution of σ_{r0} based on the assumption of independence. We invoke the central limit theorem discussed in Sec. 5.4 to conclude that σ_{r_n} has a normal distribution with a mean μ equal to that of σ_{r0} (i.e = 0) and standard deviation s equal to that of σ_{r0} divided by $\sqrt{n}$. (It is noted that this approach requires the calculation of the extreme value distribution based on pressure measurements at any point in time and not on the pressure peaks).

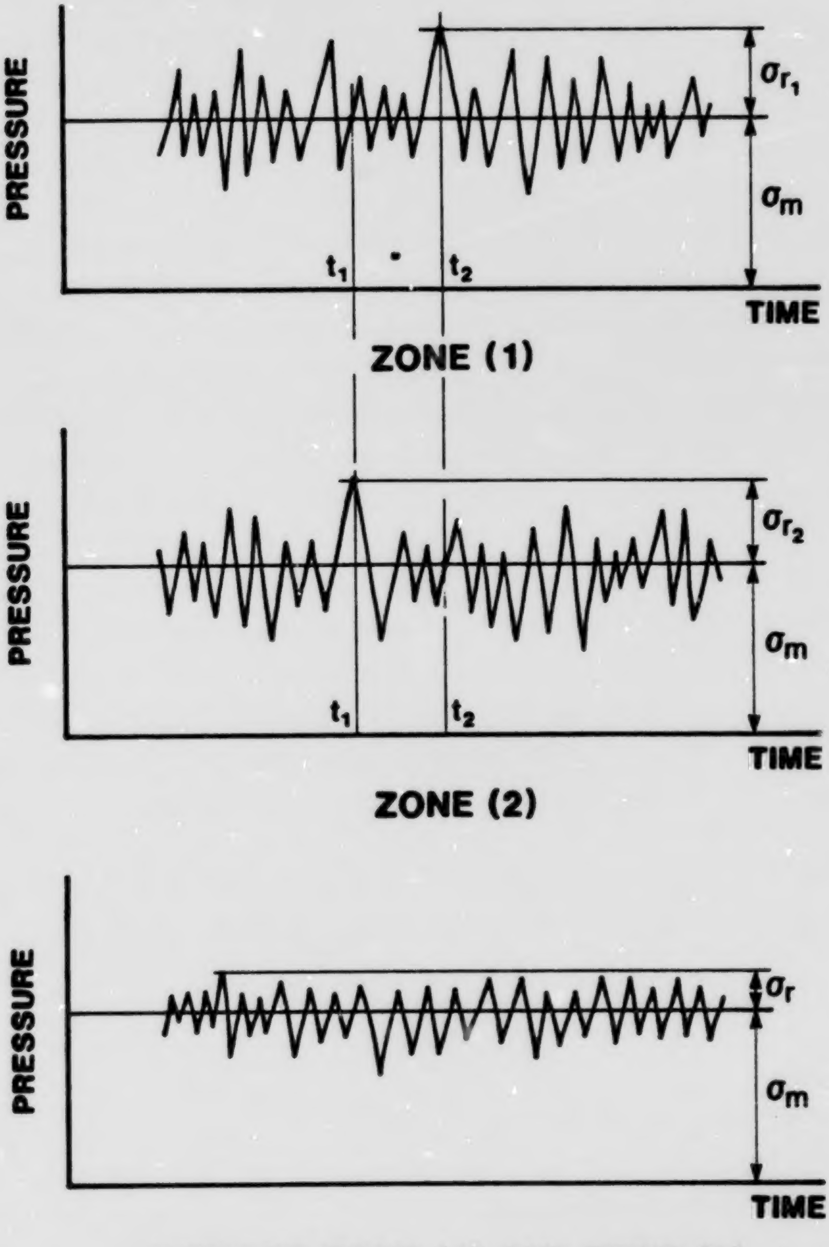

PRESSURE
σ_{r_1}
σ_m
t_1
t_2
TIME
ZONE (1)
PRESSURE
σ_{r_2}
σ_m
t_1
t_2
TIME
ZONE (2)
PRESSURE
σ_r
σ_m
TIME
AVERAGE ZONE (1) AND ZONE (2)

Fig. 6.16 The Effects of Independent Failure of the Ice on the Peak Pressure

In order to calculate the extreme value distribution of this Gaussian (normal) process, the process is discretized at regular time intervals Δt. We can then use the methodology in Sec. 5.3.4 to conclude that the extremal distribution is double exponential with parameters calculated by substituting μ, s and $k = T/\Delta t$ in Eqs. 5.16 and 5.17, provided that Δt is selected such that pressure values are independent for the pressure level being considered. In fact, this result can be shown to be valid for any stationary discrete parameter Gaussian process if the parameter value of interest is high enough to make the probability of two consecutive measurements exceeding that value negligibly small. For design purposes we are interested in high pressure values and this condition is satisfied if Δt is selected such that it is unlikely for two consecutive values to fall on the same process peak. A value of Δt in the order of magnitude of the dominant or average period of the process would clearly satisfy this condition. In the program, the user is requested to define the "discretized sampling rate" which is defined at $1/\Delta t$. This value should be as large as possible (to guarantee accuracy) but should not be large enough to violate the foregoing assumptions. A value equal to the dominant process frequency is suggested but larger values may be justified based on an actual study of the process. It is noted that other theoretical models are available for continuous processes and these can be used on the basis of proper spectral analyses of the original ice pressure process. Such work should be undertaken in the future and could lead to improved solutions.

The above gives the maximum load distribution conditional on the number of zones n, and the final distribution of the maximum pressure can be calculated from:

$$f_P(p) = \sum_{n^*}^{\infty} P_N(n)\ f_{P|N}(p,n) \tag{6.15}$$

where $n^* = A^*/A_0$ and A^* is the area of the design panel.

6.3.4 Example and Discussion

Application of the above approach requires the following information:

i) Probability distribution of the water depth (tidal changes)
ii) Probability distributions of the contact area dimensions
iii) Average rate and duration of interactions for each scenario considered

iv) Dimensions of an ice zone on which failure can be considered to occur independently from other zones

v) Pressure history data on the area defined in iv) above.

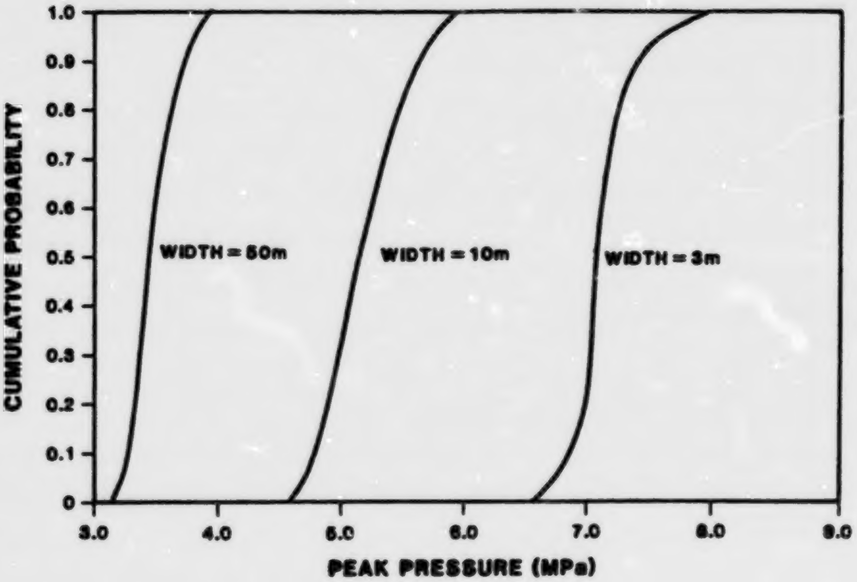
This information is currently being catalogued in a data base being generated under a separate PERD project (GEOTECH, 1988). This data can be used in the present analysis to make realistic estimates of local ice design pressures, and assess the validity of some of the assumptions and consider sensitivities based on parameteric analysis.

Sample results of the local pressures program are given in Fig. 6.17. The example considers first year ice in the winter season where the ice is constantly applying pressure on a square structure 100 m in width for a period of 250 days. The water depth is assumed constant and the ice thickness is normally distributed with μ = 1m and σ = 0.5 m. The design panel is 1m deep at the water level and has a variable width. The width of the independent zones is assumed to be three times the ice thickness. The average pressure is 2 MPa and the standard deviation 1.0 MPa. The discretized sampling rate is taken as 60/minute. Figure 6.17a gives the maximum pressure distribution for different widths. In Fig. 6.17b, the pressures which have 95 and 99% probabilities of exceedance are plotted against the width of the design area. It is emphasized that this example is based on hypothetical data and is presented only for illustration.

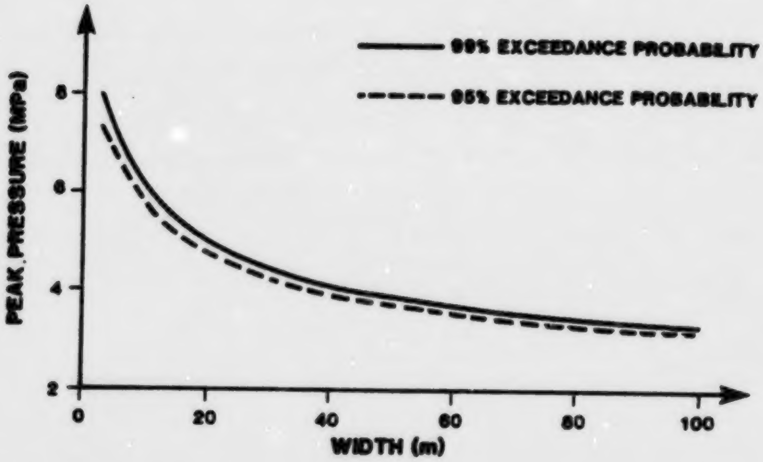
6.4 Techniques for Handling Short Data Records

6.4.1 General

The probabilistic methods described in this report derive the probability distribution of the ice loads from probabilistic descriptions of a set of input parameters. The quality of the results obtained is affected by the adequacy of the input parameter probability distributions in representing the basic uncertainties (or randomness) associated with the value of the parameter in each case. In this respect one can distinguish between two sources of uncertainty. The first is inherent in the physical process and cannot be eliminated. The size of a multi-year floe which could



a) Probability Distributions of Peak Pressure



b) Pressure Versus Contact Width

Fig. 6.17 Illustration of the Results of the Local Ice Pressure Model Using Hypothetical Data

hit a structure next season, for instance, is not known with certainty since floes of different sizes exist in the arctic and one cannot predict which of these floes will be in the vicinity of the structure. One must therefore consider all possible floe sizes with a probability measure attached to each size. This type of randomness or uncertainty cannot be eliminated and must therefore be modelled. The second type of uncertainty results from lack of knowledge. In the multi-year floe size example, the uncertainty would be further increased if the number of observations of multi-year floe sizes available are not sufficient to define the parameter distribution. It is the second type of uncertainty due to lack of knowledge that we deal with in this section.

Our knowledge of a given parameter Z is usually given in the form of a data sample $Z_1, Z_2, ..., Z_n$. In the case of floe size, Z's represent measured values of the diameters of a number of randomly selected floes. This knowledge is used in assigning a probability distribution of Z, $f_Z(z)$. A probability distribution is usually defined by its type (i.e. normal, gamma, ...) and its parameter(s). The number of parameters depends on the distribution type, but most standard distributions have two parameters which can be defined as functions of the distribution mean and standard deviation. The results of an analysis which uses the distribution $f_Z(z)$ can therefore be regarded as conditional on the distribution, i.e. on the type t and parameters $a_1, a_2, ...$ of the distribution. In the present study our final result is the maximum ice load Y. The resulting distribution of Y can therefore by written as $f_{Y|t, a_1, a_2, ...}(y)$.

Since t and $a_1, a_2, ...$ are usually estimated on the basis of data, a reasonable approach to describe uncertainty due to lack of knowledge is to consider the probability distributions of t, $a_1, a_2, ...$ In the following we will concentrate on techniques for making probabilistic statements regarding distribution parameters.

6.4.2 The Characterization of Uncertainty Due to Lack of Knowledge

Consider the case where one is interested in uncertainty due to lack of knowledge regarding a certain basic random model parameter Z. Also assume that we have selected the distribution mean A of $f_Z(z)$ which will be described itself as a random quantity to represent the uncertainty due to lack of knowledge. $f_Z(z)$ can then be written as $f_{Z|A}(z,a)$. In the process of calculating the ice load, we use the parameter Z to calculate other quantities. For example, we use the floe diameter to calculate the load Y resulting from one collision, thus making Y also conditional on the value of A. Y is then used to calculate the maximum load for a given scenario and so on until the final maximum load probability distribution is reached, and is in turn conditional on the parameter A.

It is possible initially to combine the uncertainty about A (due to lack of knowledge) and about Z (due to randomness) using the rule of total probability. This gives:

$$f_Z(z) = \int_{\text{all } a} f_{Z|A}(z,a) \quad f_A(a) \; da \tag{6.16}$$

$f_Z(z)$ calculated in this manner combines both types of uncertainty and gives one's best judgment regarding Z based on the amount of data available. Different methods for selecting $f_A(a)$ and updating it as more information becomes available can be found in Raiffa and Schlaiffer (1961). The use of this approach would result in solutions which reflect the degree of belief embodied in $f_Z(z)$. However, it has the disadvantage of losing the capability to distinguish between the effect of parameter randomness and the effect of lack of knowledge.

To overcome the above mentioned shortcoming, one could carry the uncertainty regarding A all the way through the analysis so that the final result will be conditional on A. One can then exercise judgment regarding this uncertainty only in making the final selection of the design load. The following discussion will concentrate on this approach giving methods of making probabilistic statements regarding distribution parameters as well as the final, results based on the amount of data available.

6.4.3 Distribution Parameter Estimation

There are several methods for estimating distribution parameters (Benjamin and Cornell, 1970). One simple and common method is to use the moments of the data (e.g. mean and standard deviation) as estimates of the distribution moments. This method has been used in the data analysis of Chapter 3. Consider a set of n data z_1,

$z_2, \ldots, z_n$ points regarding the value of Z. Assume that the parameter A represents the distribution mean and B the distribution standard deviation. It is intuitively acceptable to use the sample mean

$$\bar{z} = \frac{z_1 + z_2 + \ldots + z_n}{n} \tag{6.17}$$

as an estimate of A, and the sample standard deviation

$$\sigma_z = \sqrt{\frac{\sum_{i=1}^{n} (z_i - \bar{z})^2}{n}} \tag{6.18}$$

as an estimate of B. Now consider $\bar{z}$ (the sample mean) itself as a random quantity. As a function of a set of random quantities (Eq. 6.17) information regarding $\bar{z}$ as a random quantity can be derived on the basis of information regarding $z_1, z_2, \ldots, z_n$. We know that all the sample points $z_1, z_2, \ldots, z_n$ belong to the distribution $f_Z(z)$ and assume that the sampling is carried out randomly such that the values of $z_1, z_2, \ldots, z_n$ are independent. Under these conditions it can be shown that the expected value of the sample mean is equal to the mean of the original distribution of Z and that the standard deviation of $\bar{z}$, $\sigma_{\bar{z}}$ is given by:

$$\sigma_{\bar{z}} = \frac{\sigma_z}{\sqrt{n}} \tag{6.19}$$

Since we assume that $\bar{z}$ is an estimator of A we can than use the information derived regarding the mean and standard deviation of $\bar{z}$ to make probabilistic inferences regarding A. (We avoid the philosophical controversy regarding whether A itself is a random quantity or a "fixed but unknown parameter" since it does not have any practical implications for data-based analyses). Chebyshev's inequality can be used to achieve this for the above mentioned mean value regardless of the type of distribution. Chebyshev's inequality states that:

$$p\ (\bar{z} - h\frac{\sigma_z}{\sqrt{n}} \leq A \leq \bar{z} + h\frac{\sigma_z}{\sqrt{n}}) \geq 1 - \frac{1}{h^2} \tag{6.20}$$

which gives a minimum value of the probability that A lies within certain bounds. Inequality 6.20 shows that those bounds get narrower as n, the sample size increases.

Depending on the distribution of the original parameter $f_Z(z)$, the parameter distribution $f_A(a)$ may belong to some of the common distribution families. For example, if Z has a normal probability function with mean $\bar{z}$ and standard deviation σ_Z given by:

$$f_Z(z) = \frac{1}{\sigma_Z \sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{z - \bar{z}}{\sigma_Z}\right)^2\right) \qquad (6.21)$$

then the distribution mean A given a sample of n values is also normally distributed with mean $\bar{z}$ and standard deviation $\sigma_Z/\sqrt{n}$. Also if Z is an exponential distribution of the form:

$$f_Z(z) = \lambda e^{-\lambda t} \qquad (6.22)$$

then the distribution of the mean value A given a sample of n values is the gamma distribution given by:

$$f_A(a) = \frac{\lambda^n a^{n-1} e^{-\lambda a}}{\Gamma(n)} \qquad (6.23)$$

where λ is estimated from the data sample. For other parameters and distributions, the reader is referred to Benjamin and Cornell (1970). It is worth noting, however, that as n increases, the average value approaches a normal distribution regardless of the distribution type of Z (by virtue of the central limit theorem discussed in Sec. 5.4).

As an example, the thickness of a multi-year ice floe is considered. We assume that the thickness has a normal distribution with mean of 4 m and a standard deviation of 1.6 m. The distribution of the sample mean is plotted for different values of n in Fig. 6.18. The figure shows that as the sample size increases, the distribution becomes narrower. This means that the interval representing a certain probability content gets smaller.

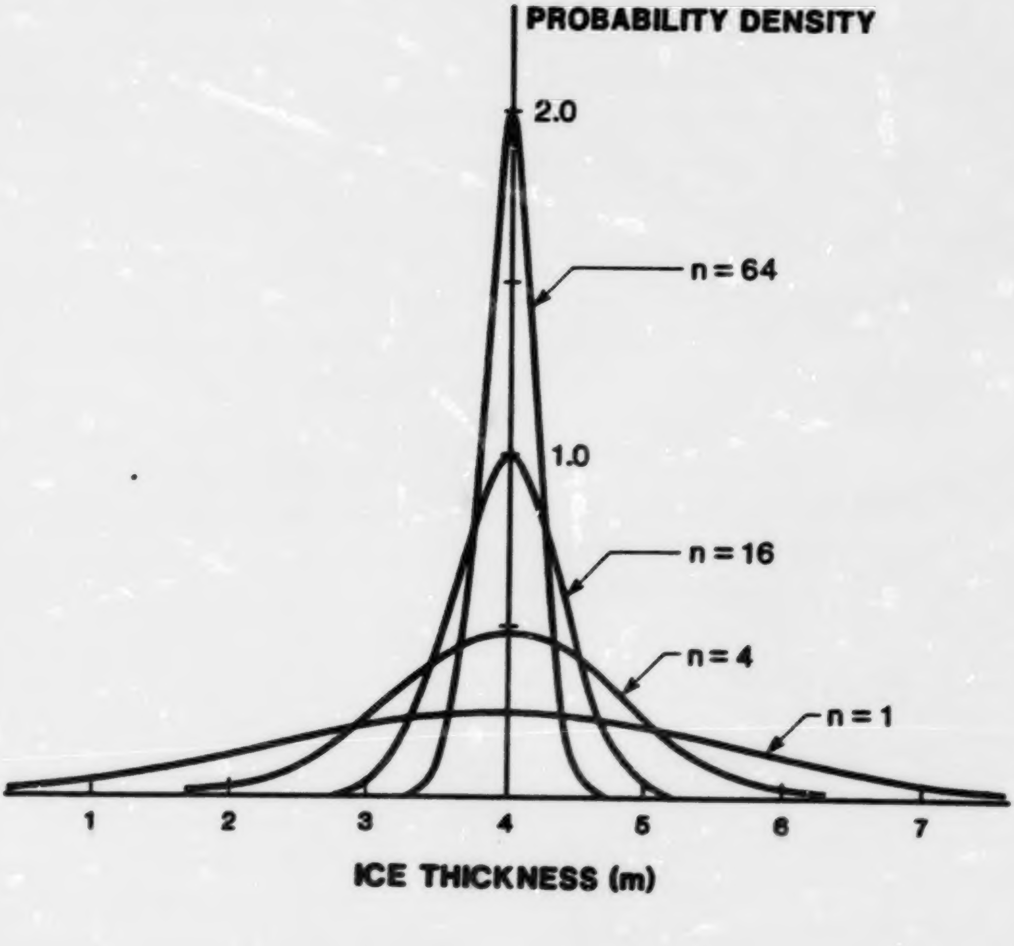


Fig. 6.18 Effect of the Sample Size on The Distribution of the Sample Mean

6.4.4 Application

The average ice thickness which has a 5% probability of being exceeded for the case of n=1 shown in Fig. 6.18 is 6.63 m. The model is run twice for multi-year floe collisions in the open water season using the point estimate of the average value 4 m, then using thickness average value with a 5% probability of exceedance for n=1. The structure is a vertical wall circular island with 120 m diameter in the Beaufort Sea. Default values were used for all other ice parameters. The resulting cumulative density functions of the maximum load are shown in Fig. 6.19. The figure gives a reflection of the uncertainty due to lack of data regarding the average value of ice thickness. The curve for fixed mean represents the design curve if the uncertainty due to lack of knowledge is ignored. The other curve should be used if one considers this uncertainty and wants to be sure that there is only 5% chance of the used design load being exceeded due to lack of knowledge regarding the mean thickness. Design curves corresponding to other levels of uncertainty can be generated using the same methodology. In fact, one can develop the probability distribution of say the 100 year load conditional on the mean ice thickness value. In the present example, the 100 year load corresponding to a fixed average ice thickness is approximately 700 MN. The 100 year loads corresponding to the ice thickness with 5% probability of exceedance for n=1 is approximately 900 MN. It is noted that the spread between the curves in Fig. 6.19 is an indication of the sensitivity of the results to the average ice thickness.

6.5 Comments

The models described in this Chapter must be seen in light of their underlying assumptions. These assumptions are clearly mentioned in the discussion and derivation of each component (Chapter 5) and of the integrated probabilistic load models in this Chapter. Extensive testing and comparisons should be undertaken in order to assess the performance of different assumptions under different conditions and identify situations which require more sophisticated modelling. For example, non-multiplicity was assumed for discrete feature collision. This means that the probability of interaction with two ice features (e.g. multiyear floes) simultaneously is negligible compared to the probability of interaction with one feature. This assumption may not be valid if the multiyear ice concentration around the structure becomes very large

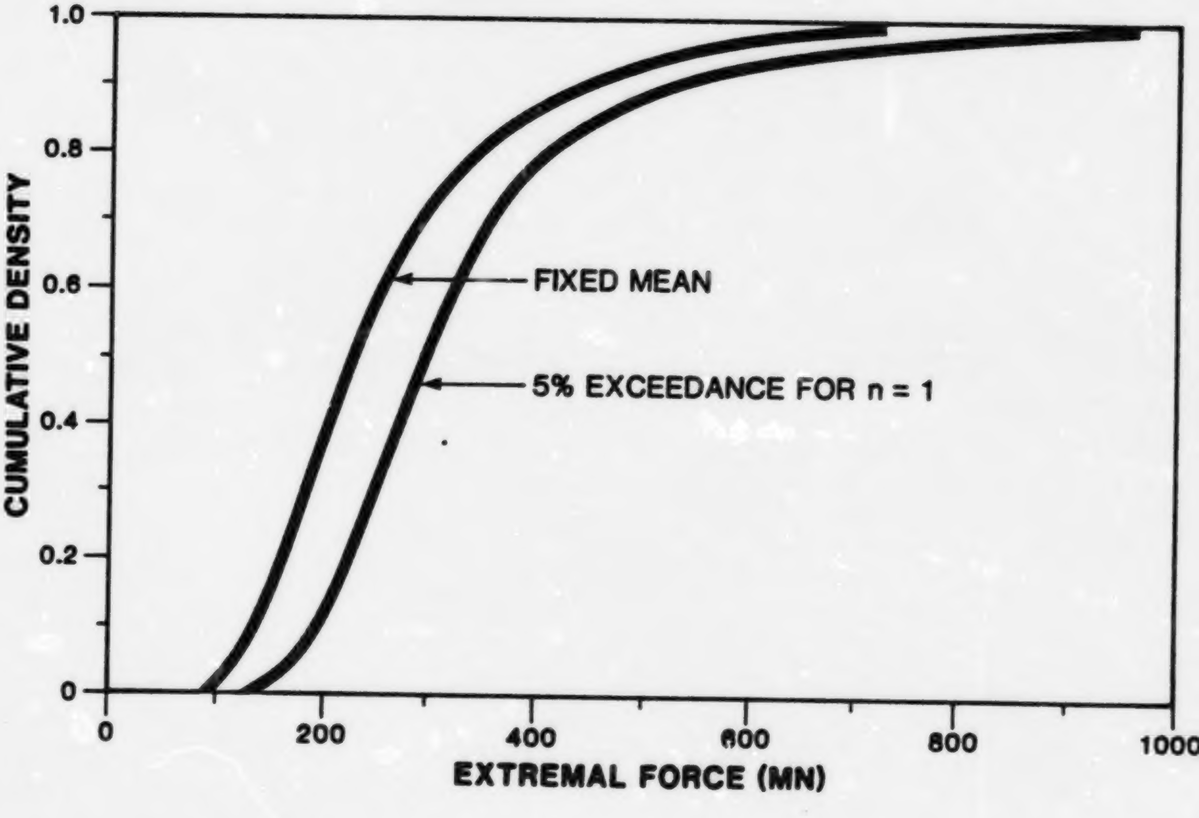


Fig. 6.19 The Cummulative Density Functions of the Maximum Load Corresponding to Different Levels of Uncertainty Regarding the Average Ice Thickness

due to several floes approaching at the same time. The assumption should then be examined in comparison to different ice movement patterns and adjusted if necessary. Also sensitivity analyses of the results to different input parameters should be undertaken to determine the quality and quantity of the data to be sought for each parameter. It is recommended that such testing and sensitivity analyses be undertaken in future studies.

CHAPTER 7

CONCLUDING REMARKS

A comprehensive probabilistic model was developed for estimating global and local ice forces on fixed offshore structures. The model considers different possible ice conditions, ice loading scenarios and features. The model is computerized in a user friendly package which accepts user defined ice parameters and structure geometry to give probabilistic descriptions of ice loads for any loading scenario or combination of scenarios. The model concentrates on probabilistic aspects and includes simplified ice-structure interaction algorithms to calculate the load values. We conclude this report by making the following remarks:

i) Much of the probabilistic modelling is based on the analysis of pressure history data as a stochastic process. Pressure measurements from full scale data are therefore viewed as essential for obtaining good estimates of force values. The model also requires such parameters as contact area geometry and contact time.

ii) The results of the model are sensitive to some environmental input parameters and it is recommended that the user use good quality data which is relevant to the location of interest. In selecting the parameter defaults provided in the model, every effort was made to select representative values on the basis of data analysis and judgment. These values, however, should not be used without re-examination since parameters can change substantially from location to location within a given geographic area. Also, there is very little public data regarding large-scale ice mechanical properties and behaviour and most of the default values are based entirely on judgment.

iii) Ice-structure interaction models used represent the state-of-the-art in force calculation models as well as some new developments where approximate models were not available. Each ice-structure interaction module is structured as a separate module in the program in order to facilitate modification as better models become available.

iv) The results show that the loads are not dominated by one scenario, but that each scenario may lead to high loads under certain conditions and for different levels of the probability of exceedance. Calculated loads from first-year ridges, for example, are of the same order of magnitude as those from multiyear floes in the Beaufort Sea. This is partly because the model used in calculating first-year ridge forces is an upper bound model which overestimates the load.

v) Monte Carlo simulation methods have been found to require a large number of iterations before stable extremal distribution can be obtained. More sophisticated methods based on structure reliability algorithms are available and could be used to replace Monte Carlo numerical methods.

The following areas were identified as future research needs:

i) The model is well suited to parametric studies and sensitivity analyses. It would be useful to carry out test runs and examine systematically the design ice load sensitivity to different parameters in selected offshore locations.

ii) The model makes use of environmental data as well as ice mechanical properties and interaction pressure histories. Several relevant computerized data bases are available for example at AES and C-CORE. Of particular relevance is the new data base being developed under the PERD program for large scale ice-structure interaction data. It would be very useful to create appropriate interface capabilities such that the program can interact directly with these data bases. This would guarantee the use of the latest information as these data bases are updated without the need for manual data processing and preparation.

iii) There is a need to investigate more sophisticated statistical techniques which may be used to replace the time consuming Monte Carlo simulations approach. Structural reliability approaches exist which are very useful in this regard and are capable of developing load distributions in a fraction of the time needed when the Monte Carlo technique is used.

iv) First year ridge interactions are very common in some geographic locations. Due to the high rate of interaction with these features, the maximum annual load could be very high even though the average load during each interaction is low. Force calculations for this scenario have not received much attention and have been based on upper bound methods. Refinement of these models and the development of new approaches for this scenario could be useful in improving design load estimates.

v) Summer areal feature interaction produce high load values. These may be reduced if load relief by ice feature splitting due to crack propagation is accounted for. Models for this failure mode of ice should be developed.

vi) The local pressure model developed was based on the discretization of the random process representing pressure history data at user defined intervals. Further research is required to give quantitative guidance on the appropriate interval length for this approach and to investigate other continuous process approaches which may be more appropriate. Such work requires a definition of the spectral characteristics of the process and can be undertaken using large-scale pressure data. This work could lead to the incorporation of several extremal approaches in the local pressure model, one of which is to be selected on the basis of the appropriate stochastic process parameters for the scenario considered. These refinements could lead to significant improvements in the selection criteria for local ice pressures.

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PROBABILISTIC FRAMEWORK FOR ICE LOADS ON FIXED MARINE STRUCTURES

Volume 2 - User's Guide to Ice Load Computer Package

July 1988

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Calgary, Alberta

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Marine Product Line, Headquarters
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17. Abstract

Probabilistic models were developed for the estimation of global and local ice for fixed marine structures. The models produce load descriptions which are compatible with probability-based design code requirements and can thus be used in selecting design criteria. Ice loading is estimated by using probabilistic environmental inputs in appropriate ice-structure interaction models to produce a probabilistic distribution of the load. This is then used in extremal models to calculate the probability distribution of the maximum annual load or pressure which is the basis for selecting design loads. The study included the statistical analysis of environmental data and ice mechanical properties in order to obtain the best probabilistic descriptors of input parameters to the model. Ice-structure interaction models were selected from available approaches and new models were developed areal ice feature collisions in open water and winter conditions. The probabilistic models were developed include stochastic process models for different ice load scenarios, models for the exposure levels of the structure to a given scenario and models for estimating the load magnitude during each interaction event. Extremal models for the discrete Poisson process and for stationary continuous processes are also used. These components were included in integrated models and computer programs for calculating global loads and local pressures and techniques for dealing with short data records were also developed. This volume is a user's guide to the Ice Load computer package.

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17. Résumé

Des modèles probabilistes ont été construits pour l'estimation des charges gglobales et locales de la glace auxquelles sont exposées les structures fixes en mer. Ces modèles produisent des descriptions de la charge qui sont compatibles avec les exigences des codes de conception reposant sur les probabilités et ils peuvent donc être utilisés pour la détermination des critères de conception. On estime la charge de la galce en introduisant des données environnementales probabilistes dans les modèles appropriés de l'interaction glacestructure afin d'obtenir une distribution probabiliste de la charge. On utilise ensuite cette distribution dans des modèles extrêmaux pour calculer la distribution des probabilités de la charge, ou pression, annuelle macimale ès partir de laquelle sont déterminées les charges théoriques. L'étude a comporté des analyses statistiques des données environnementales et des propriétés mécanique de la glace pour la détermination des meilleurs descripteurs probabilistes des paramètres d'entrée du modèle. On a choisi des modèles d'interaction galcestructure à partir d'approches disponibles et on a élaboré de nouveaux modèles pour les collisions avec la glace dans une zone en eau libre et en hiver. Les modèles probabilistes construits comprennent des modèles de processus stochastiques pour différents scénarios quant à la charge de la glace, des modèles pour le niveaux d'exposition de la structure à un scénasrio donné et des modèles pour l'estimation de l'importance de la charge durant chaque interaction glace-structure. Des modèles extrêmaux pour le processus discret de Poisson et pour des processus continus stationnaires sont également utilisés. Ces composantes ont été introduites dans des modèles intégrés et des programmes informatiques pour le calcul des charges globales et des pressions locales. Des techniques ont également été mises au point pour les statistiques couvrant une courte période. Il constitue un guide pour les utilisateurs d'un progiciel pour la charge de la glace.

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PREFACE

This report is one of several reports on the research work in the field of marine engineering, identified and managed by the Marine Product Line and Technology Resources groups of Public Works Canada, with funds provided by the Interdepartmental Panel on Energy Research and Development (PERD).

PERD was established in 1974 to coordinate research on energy by the Federal Government with objectives to provide, in conjunction with efforts in the private sector and the provinces, the technical basis for:

- maintaining oil self-sufficiency over the short term, in view of dwindling conventional supplies;
- developing a diversified energy economy, less dependant on oil and gas in the mid-term; and
- making Canadians less reliant on non-renewable energy sources in the long term.

The research work undertaken by Public Works Canada in Marine Engineering with funds from PERD has been directed particularly toward the following two main topics:

1. Ice/Structure Interaction
2. Construction and Towing of Reinforced Concrete Caissons in the Arctic.

This report is being published with a view to enhancing the technology in the field of Marine Engineering and contributing toward the objectives of PERD.

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CHAPTER 1

INTRODUCTION

1.1 Purpose of System

The purpose of this computer package is to develop probabilistic descriptions of the maximum annual ice loads and pressures on a fixed offshore structure, due to a user defined combination of ice loading scenarios. The theory and methodology are described in detail in Volume I (Study Description) of this report.

1.2 Overall Structure

The package consists of two parts, the first for calculating global forces and the second for local forces.

The global load part consists of three separate programs as follows:

1. INPUT: an input program which accepts environmental data and creates a data file.
2. MAIN: a main program which performs the calculation using the data created by INPUT, and creates output results.
3. OUTPUT: an output program which processes the results of MAIN.

The local force part consists of one program, LOCAL.

1.3 System Features

The package has the following features:

1. All programs are fully interactive with a self explanatory input format.
2. INPUT has a built-in set of input parameter default values. The user has the option of modifying any of these default values.
3. The package is organized in a modular fashion with each element of the problem treated in a separate subroutine. This allows future replacement or modification of different modules with minimal effort.
4. All three global load programs have data retrieval facilities to minimize computing time losses in case of system failure.
5. All screen inputs are checked for the number and type (i.e. real or integer) of data entries to eliminate execution errors due to accidental keyboard errors.
6. Reasonable bounds are set for all input parameters to ensure the consistency and accuracy of input data. The allowable parameter ranges are wide enough to allow sensitivity analyses.
7. Internal documentation giving the purpose of each routine and the definition of its input and output parameters is included in the code.

1.4 Scope

i) Structural Geometries

The following structural geometries are considered:

1. Vertical sided structures with cylindrical sides (i.e. circular in plan) or flat sided (i.e. polygonal in plan). A polygon can have up to 20 sides and is defined by the coordinates of its apexes with respect to any two perpendicular axes through its centre. The apexes are to be entered sequentially in a clockwise direction starting with an arbitrary apex. The polygon must be concave with respect to its centre.

2. Upward and downward breaking cones. Cones are not allowed in the landfast ice zone or in the Grand Banks area.

ii) Ice Load Scenarios

The seasons and ice load scenarios considered in the global load package are as illustrated in Table 1.4.1. The scenarios are dealt with in the program in the same order given in the table. This order is significant for the use of data retrieval facilities, and this will be discussed further in Sections 2.2 and 3.6. In INPUT, the user has the option of specifying any one scenario or combination of scenarios to be considered in the run being performed. For the scenarios considered, OUTPUT allows the user to extract the probabilistic description for the load per individual event and the extremal load for each scenario separately, as well as for the extremal load due to any scenario combination.

In the local load program, scenarios are only identified by number. The user can compound the pressure distributions due to any number of scenarios.

Table 1.4.1. Ice Load Scenarios

SEASON	LANDFAST ICE ZONE	ACTIVE ICE ZONE
Partial Ice Cover	- first year ridges - level ice - multi-year floes - icebergs - ice islands - ice island fragments	- first year ridges - level ice - multi-year floes - icebergs - ice islands - ice island fragments
Full Ice Cover	- level ice	- first year ridges - level ice - multi-year floes - icebergs - ice islands - ice island fragments
Open Water	- first year floes - multi-year floes - icebergs - ice island fragments - ice islands	- first year floes - multi-year floes - icebergs - ice island fragments - ice islands

CHAPTER 2

FILES AND FILE HANDLING

2.1 File Handling Options

The programs INPUT, MAIN, OUTPUT and LOCAL provide two file handling options, namely internal file handling from within the program and external file handling using job control language. The appropriate choice of either option depends on the operating system of the computer used, as will be explained in this section. The option to be implemented is determined by the value of the parameter INTFN in subroutine UNITS. This subroutine exists in all four programs (INPUT, MAIN, OUTPUT and LOCAL) and the value of INTFN must be the same in all four programs. INTFN defines the file handling option as follows:

i) INTFN = 1 File handling from within the program:

In this option, the user will be asked interactively to define the names of all files used (except scratch files which are only used internally and do not contain any useful output upon program termination). The implementation of this option requires opening and closing files from within the program, using the Fortran statements OPEN and CLOSE. The user must, therefore, ensure that the operating system of the computer hardware used allows for file handling from within the program. If this option is used, the parameter NFCHAR in subroutine UNITS should be set equal to the maximum allowable number of characters for a file name. This should be done in all four programs (INPUT, MAIN, OUTPUT and LOCAL).

ii) **INTFN = 0** External file handling:

In this option, files are set using job control language externally from the program. INTFN = 0 will cause the program to bypass file name definition and file OPEN and CLOSE statements. Files will be given names which depend on the unit number used for each file (see Section 2.4). A file on unit 10, for example, will be automatically given the name FILE10. This option must be used if the operating system of the computer hardware used does not allow opening and closing files from within the program (e.g. IBM main frame computers).

The default value of INTFN is 1.

2.2 File Types, Structure, and Usage

i) **Input File:** Used for sequential READ of formatted input data.

ii) **Output File:** Used for sequential WRITE of formatted output data

iii) **Back-up File:** Back-up files are sequential formatted files used in INPUT and OUTPUT to provide a data retrieval facility which reduces interactive running time. This facility allows bypassing the interactive input of a portion of the data by retrieving the information from a back-up file created from a previous run. This option is useful if a certain amount of input data is the same for both runs. The use of the back-up file depends on the data retrieval status (i.e. on or off). This is best illustrated by an example. Assume that a new run of program INPUT is to be performed with no data retrieval (say RUN1). The back-up file in this case is a new file which is used as a WRITE file and, at the end of the run, contains all screen messages and user's responses. Assume that the user wishes to perform a new run of INPUT (RUN2), which has a certain amount of information in common with RUN1. The user can, in this case, edit the back-up file created by RUN1 to remove all data starting with and including the first user's response which is not the same as for RUN2. RUN2 can then be started with the retrieval mode on, and the back-up file defined as the back-up file obtained from RUN1 after editing as discussed above. In the retrieval mode, the back-up file will be used as a READ file from which the user's responses will be retrieved without displaying the corresponding messages. When the end of the back-up file is reached (i.e. beginning of new input specific to RUN2), the retrieval status will be automatically switched to off, and messages will start to appear on the screen to prompt the user to enter the rest of the input data. At the end of RUN2, a new back-up file will be created which contains complete back-up information for RUN2. Back-up files can also be used to retrieve informaton from runs which are interrupted due to system or execution errors.

iv) **Data Base File:** This is a sequential unformatted file which contains the results of the computation carried out by MAIN. Each entry to this file is defined on two data records. The first data record contains three attribute parameters denoting the key, size and type of the entry, while the second record contains the entry itself. each entry is either a character variable, an integer array, or a real array. The above-mentioned attribute parameters of each entry are defined as follows:

- key: defines the meaning of the entry (e.g. run title, file name, average value of force in given scenario, cumulative distribution function of force in given scenario, etc.).
- size: defines the number of characters (1 to 72) for a character variable or the dimension of the array (1 to 201) for a real or integer array.
- type: defines whether the data is an integer array (=1), a real array (=2), or a character variable (=3).

The data base file is accessed by MAIN in the same manner in which the back-up files are accessed by INPUT and OUTPUT (as explained in (iii) above). This depends on the re-start status. The data base file is accessed as a WRITE file if the re-start status is inactive. If re-start is active, the program uses the data base file as a READ file until the end of file is reached and then switches its status to a WRITE file. Data is transferred to and from the data base at the end of the calculations for each scenario. The scenarios are dealt with in the same order shown in Table 1.1. The re-start option can be used to add specific scenarios to the data base. Assume, for example, that a run was carried out to cover all partial ice cover loading scenarios (see Table 1.1). If the user wishes to add the full ice cover scenarios to the data base then a new input file should be created, which contains the input parameters for both the break-up and winter scenarios. MAIN can then be run in the re-start mode using the new input file and the data base file created by the previous partial ice cover run. The program will automatically bypass the calculations made in the previous run, carry out the calculations for the additional scenarios (i.e. winter in this case), and create a new data base which contains both break-up and winter results. Summer can be added to this new data in a similar manner. This segmentation is useful to meet the CPU time limitations per run which may be imposed.

It is emphasized that the sequence of calculation of load scenarios is as shown in Table 1.1 and this order should be followed if a run is to be segmented in this manner. Also, if a run is interrupted due to system related reasons, one need not re-run the whole job. The run can be re-started using the same input file and the portion of the data base available from the previous interrupted run. It is noted that unlike the back-up file usage for INPUT and OUTPUT, the data base file is an unformatted file which cannot and need not be edited.

v) **Scratch Files:** these are used internally in the program as WRITE/READ files and are deleted at the end of the program execution.

2.3 Units

The file unit numbers are assigned in subroutine UNITS, which exist in each of the programs INPUT, MAIN, and OUTPUT. The default unit numbers used are in the range of 10 through 17. On some computer systems, some unit members are reserved for specific devices (e.g. screen or printer). The user should edit subroutine UNITS in each of the three programs (INPUT, MAIN, OUTPUT and LOCAL), and if necessary, change the values of the unit numbers to ensure that no such restrictions apply to the unit numbers used. This need only be done in subroutine UNITS. Tables 2.3.1, 2.3.2 and 2.3.3 detail the units used in each of the four programs with a description of the type and usage of each file, for the cases of INTFN = 0 and INTFN = 1, respectively (see Section 2.1).

Table 2.3.1. Unit Numbers and Corresponding Files for Global Load Package (INTFN = 0)

PROGRAM	UNIT	FORM	USAGE
INPUT	NUOUT	Formatted	- output file
	NUBU	Formatted	- output back-up file for normal mode of execution (i.e. no retrieval) - input back-up file for retrieval mode of execution.
	NUSCBU	Formatted	- output back-up file for retrieval mode of execution
	NUSCRA	Formatted	- scratch file
MAIN	NUIN	Formatted	- input file
	NUOUT	Formatted	- output file
	NUDUMP	Formatted	- output file
	NUDB	Unformatted	- output data base file for normal mode of execution (i.e. re-start off) - input data base file for re-start mode of execution
	NUSCDB	Unformatted	- output data base file for re-start mode of execution
	NUSCRA	Formatted	- scratch file
OUTPUT	NUOUT	Formatted	- output file
	NUBU	Formatted	- output back-up file for normal mode of execution (i.e. no retrieval) - input back-up file for retrieval mode of execution.
	NUSCRB	Formatted	- output back-up for retrieval mode of execution.
	NUDB	Unformatted	- input data base file
	NUSCRA	Formatted	- scratch file

Table 2.3.2. Unit Numbers and Corresponding Files for Global Load Package (INTFN = 1)

PROGRAM	UNIT	FORM	USAGE
INPUT	NUOUT	Formatted	- output file
	NUBU	Formatted	- output back-up file for normal mode of execution (i.e. no data retrieval) - input/output back-up file for retrieval mode of execution
	NUSCRA	Formatted	- scratch file
	NUSCBU	Formatted	- scratch file
MAIN	NUIN	Formatted	- input file
	NUOUT	Formatted	- output file
	NUDUMP	Formatted	- output file
	NUDB	Unformatted	- output data base file for normal mode of execution (i.e. re-start off) - input/output data base file for re-start mode of execution
	NUSCDB	Unformatted	- scratch file
	NUSCRA	Formatted	- scratch file
OUTPUT	NUOUT	Formatted	- output file
	NUBU	Formatted	- output back-up file for normal mode of execution (i.e. no data retrieval) - input/output back-up file for retrieval mode of execution
	NUDB	Unformatted	- input data base file
	NUSCRA	Formatted	- scratch file
	NUSCRB	Formatted	- scratch file

Table 2.3.3. Unit Numbers and Corresponding Files for Local Pressure Program (INTFN = 0 and INTFN = 1)

UNIT	FORM	USAGE
NUOUT1	Formatted	- Summary output file
NUOUT2	Formatted	- Distribution output file
NUSCRA	Unformatted	- Scratch file

2.4 Input/Output Organization

The organization of the input and output for each program in the global load package and the manner in which these files interconnect is shown in Figures 2.4.1 and 2.4.2 for INTFN = 0 and INTFN = 1 (see Section 2.1) respectively. The following comments are noted:

i) The output file of INPUT is used as input file for MAIN. The same file is connected to NUOUT while running INPUT and to NUIN while runing MAIN. This should not cause any confusion, since unit numbers are internal parameters in each program. The connection should be made through the file name. For example, for INTFN = 1, INPUT can be run with an output file name of "CASE1". In this event, MAIN should be run with an input file name of "CASE1". For INTFN = 0 (see Section 2.1), this connection should be done externally using Job Control Language.

ii) The output data base file of MAIN is used as input data base file for OUTPUT. The connection between these files should be made as described under i) above. It is noted that for INTFN = 0 (see Section 2.1), the output data base file of MAIN is given on NUDB for normal execution (without re-start), and on NUSCDB for re-started runs.

For the program LOCAL the file organization is quite simple and is adequately explained in Table 2.3.3. The program LOCAL uses only screen input and does not have any retrieval facilities because the calculations and running are not time consuming.

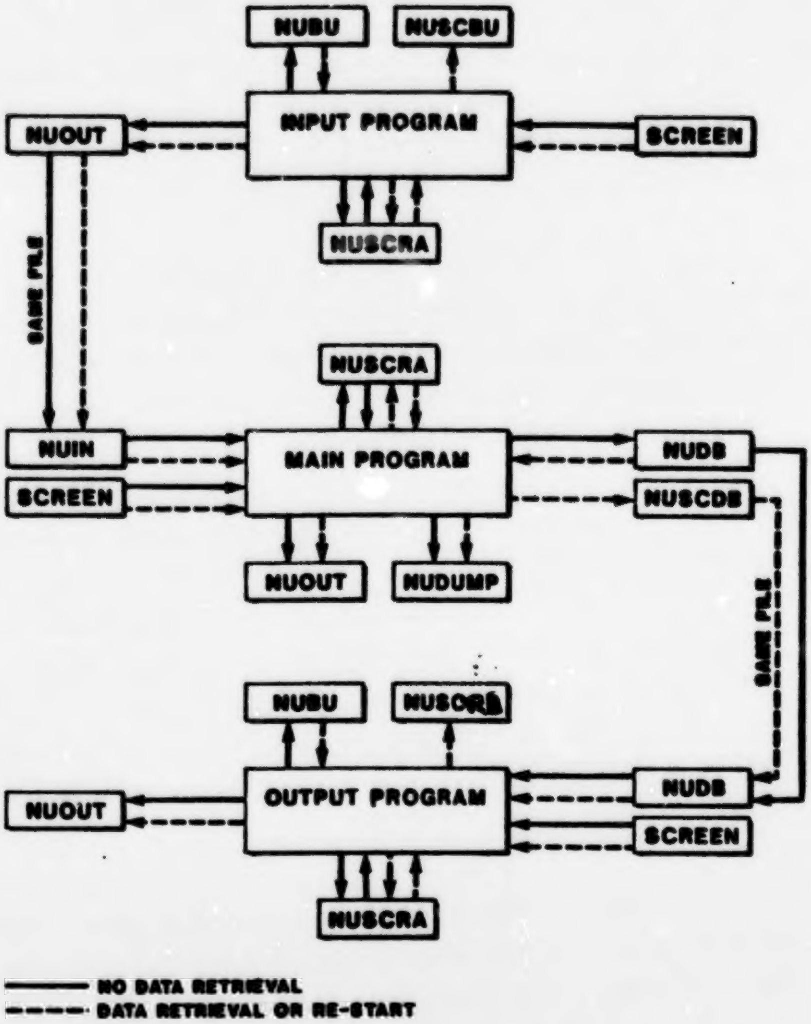
NUBU
NUSCBU
INPUT PROGRAM
NUOUT
SCREEN
NUSCRA
SAME FILE
NUSCRA
NUIN
MAIN PROGRAM
NUDB
SCREEN
NUSCDB
NUOUT
NUDUMP
SAME FILE
NUBU
NUSCRA
OUTPUT PROGRAM
NUDB
NUOUT
SCREEN
NUSCRA
NO DATA RETRIEVAL
DATA RETRIEVAL OR RE-START

Figure 2.4.1. File Organization and Usage for INTFN = 0 (External File Handling)

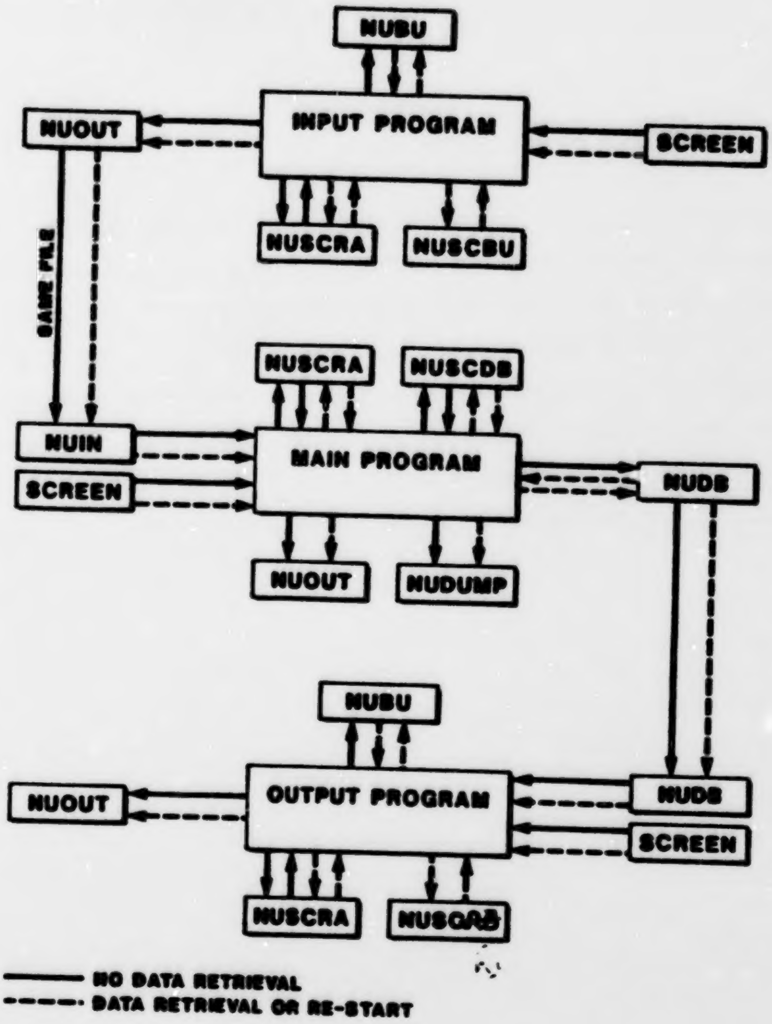
NUBU
INPUT PROGRAM
NUOUT
SCREEN
NUSCRA
NUSCBU
SAME FILE
NUSCRA
NUSCDB
NUIN
MAIN PROGRAM
SCREEN
NUDB
NUOUT
NUDUMP
NUBU
OUTPUT PROGRAM
NUOUT
NUDB
SCREEN
NUSCRA
NUSCDB
NO DATA RETRIEVAL
DATA RETRIEVAL OR RE-START

Figure 2.4.2. File Organization and Usage for INTPN = 1 (Internal File Handling)

CHAPTER 3

RUNNING THE PROGRAMS

3.1 Introduction

In this chapter, the preparatory steps required before running the programs are explained (Section 3.2), and running the programs is discussed in Sections 3.3 to 3.6. Using the re-start and data retrieval options for the global load package is also demonstrated in Section 3.7. The method of running the program is illustrated by an example. It is recommended that the user follow the steps discussed in this chapter in order to reproduce the example results. This will help familiarize the user with running the program and will serve as a verification run by comparing the results obtained to those contained in this user's guide..

3.2 Preparation

1. Read programs from disk. Each program is given in two files,
   - a) a source file containing fortran listings of the program, and
   - b) a code file containing an auxiliary package that is needed for running the program.

   Note that two versions of each of the programs MAIN and LOCAL are given. One of these versions uses IMSL statistical routines while the other uses equivalent DnV (Canada) routines contained in the auxiliary code file for each program. The user has the choice of using either version.

2. Edit each of the four source programs and locate subroutine UNITS. The following steps should be followed to ensure that subroutine UNITS is properly set:

   - i) check the value of INTFN and change it if necessary to correspond to the operating system of your computer (see Section 2.1 for details). The value of INTFN should be the same in all four programs (INPUT, MAIN, OUTPUT and LOCAL).

   - ii) if INTFN = 1 (i.e. file handling from within program), the parameter NFCHAR in subroutine UNITS should be set equal to the maximum permissible number of characters for a file name. The default value is NFCHAR = 15. NFCHAR should have the same value in all four programs.

   - iii) all unit number assignment statements should be checked and, if necessary, changed to ensure that they are all permissible unit numbers (see Section 2.3).

   It is emphasized that the above steps i), ii) and iii) should be carried out for all four programs.

3. For the program MAIN, the maximum number of simulations per scenario is 002500. This is defined in parameter statements in each of the subroutines FLOE, BERG, SILD, ACTLVL, LSTLVL and FYRIDG. You may wish to increase this number to obtain more simulations, or decrease it to meet computer system limitations. If this is the case, edit program MAIN and locate the statemnt PARAMETER (NSMAX = 002500) in each of the above-mentioned subroutines and change the value 002500 to the desired number. NSMAX must be the same in all routines in MAIN.

   The same limitation applies to LOCAL where one PARAMETER (NSMAX = 002500) statement is located in subroutine LOCDIS and can be changed as mntioned above.

4. Compile programs INPUT, MAIN and OUTPUT to obtain a code file for each program.

5. Link each program code file with the corresponding auxiliary code file provided.

3.3 Running INPUT

The purpose of INPUT is to create a data file which will be later used by MAIN to perform global ice load calculations. The program also creates a back-up file which can be used later to facilitate future runs (see Section 2.2). INPUT is fully interactive, and is self explanatory. Once the execution of the program is started, the user should answer the appropriate questions regarding the location and geometry of the structure, and the seasons and scenarios to be considered in the run. Environmental parameters required for the problem will be displayed in a series of menus which give the default values of these parameters. By following the program instructions, the user can change the values of any of these environmental parameters as desired. A value of -99 appears on the screen for any undefined parameter. Such value must be changed to the appropriate value of the parameter. The program will give an error message and ask for redefinition of any parameter with an undefined value.

Probabilistic parameters are defined by the mean, standard deviation, probability density function and lower bound. The mathematical density functions available in the current version are:

- normal
- lognormal
- beta
- uniform
- gamma
- exponential

In addition, any parameter can be given a fixed (deterministic) value, or described by a numerical cumulative distribution which can be obtained by digitizing a set of data. The latter option is useful in cases where data is available to which a mathematical density function cannot be fitted. A numerical distribution can be described by up to 20 points, each defined by a given value of the parameter and the corresponding cumulative probability. The parameter values must be given in an increasing order, and the cumulative probabilities must be monotonically increasing between 0 and 1.

It is important to note that parameter probabilistic descriptions must be defined for the full range of possible values of the parameter (0 to ∞ in most cases). The user can set lower bounds for each parameter below which the values of the parameter are not to be considered. The input distribution parameters, however, must be based on the full range of parameter values. The parameters of truncated data sets (e.g. ridge height data given only for ridges higher than 0.7 m say), cannot be used directly in the model. A correction must be applied to infer the data parameters for the full parameter range (i.e. for all ridge heights between zero and ∞ in the above-mentioned example) from those of the truncated data set.

An example run is given in the following pages. The example is for a circular vertical structure in the pack zone of the Canadian Beaufort Sea. The scenarios considered in the example are first-year ridges, level ice, and multi-year floes in the full ice cover season. The program defaults are used for all parameters. The example is displayed on the next few pages as follows:

i) pages 3-3-3 to 3-3-7 show a print out of the output back-up file created by this run of INPUT. This gives a record of the program's prompts and user's responses, and

ii) pages 3-3-8 to 3-3-10 shows a print out of the output data file of INPUT created by this run.

```
                 ****** P R O G R A M   I N P U T *****

              INTERACTIVE PRE-PROCESSOR FOR PROBABILISTIC

                           ICE LOAD PROGRAM

              DEVELOPED BY DET NORSKE VERITAS (CANADA) LTD.

                        RELEASED MARCH,1988




ENTER RUN TITLE (MAX. 60 CHARACTERS)

DEMONSTRATION


INPUT GEOGRAPHIC AREA

1 = BEAUFORT SEA

2 = GRAND BANKS

3 = OTHER

1


INPUT ICE ZONE

1 = LANDFAST ZONE    2 = PACK ZONE

2


INPUT WATER DEPTH (M)

40


INPUT DISTANCE OFFSHORE (KM)
INPUT TYPE OF STRUCTURE

1 =VERTICAL      2 = CONICAL

1


SHAPE OF STRUCTURE IN PLAN

1 = CIRCULAR      2 = POLYGONAL

1


INPUT STRUCTURAL DIAMETER IN METERS

100



STRUCTURAL GEOMETRY USED IS AS FOLLOWS:


INDEX    PROPERTY                            CURRENTLY USED


 1.      SHAPE                               VERTICAL

 2.      SHAPE IN PLAN                       CIRCULAR

 3.      DIAMETER                             100.00   M


ENTER INDEX OF LINE YOU WISH TO CHANGE (0=NONE)

0



POSSIBLE ICE CONDITIONS (SEASONS) ARE AS FOLLOWS:


 1. OPEN WATER

 2. FULL FIRST YEAR ICE COVER
 3. PARTIAL FIRST YEAR ICE COVER


ENTER 1 (=CONSIDERED) OR (0=NOT CONSIDERED) FOR EACH OPTION

3 ENTRIES EXPECTED

0,0,1  ←



BOUNDARY DATES BETWEEN DIFFERENT ICE CONDITIONS ARE AS FOLLOWS:


INDEX  PARAMETER                          MEAN        STD. DEV. DISTRIBUTION

                                      (DAY/MONTH)     (DAYS)


 1.    BEGIN. OF PARTIAL FY COVER    22/  6         13.10    NORMAL

 2.    END OF PARTIAL FY COVER        6/  7         22.90    NORMAL


ENTER INDEX OF LINE YOU WISH TO CHANGE (0=NONE)

0


POSSIBLE LOADING SCENARIOS ARE AS FOLLOWS:


 1. FIRST YEAR LEVEL ICE

 2. FIRST YEAR RIDGES

 3. MULTIYEAR FLOES

 4. ICE BERGS

 5. ICE ISLANDS

 6. ICE ISLAND FRAGMENTS


ENTER 1 (=CONSIDERED) OR 0 (=NOT CONSIDERED) FOR EACH SCENARIO

6 ENTRIES EXPECTED

1,1,1,0,0,0
```

```
THICKNESS OF FY ICE =       1.50       M

DO YOU WISH TO CHANGE

1 = YES        0 = NO

0



PARTIAL ICE COVER FY RIDGE PARAMETERS USED ARE AS FOLLOWS :

INDEX  PARAMETER           UNITS       MEAN    STD. DEV.  DISTRIBUTION


 1.    RIDGE COVERAGE      PERCENT 30.0000         .0000   DETERMINISTIC

 2.    RIDGE HEIGHT        M            .9000      .9000   EXPONENTIAL

 3.    RIDGE LENGTH        M        150.0000       .0000   DETERMINISTIC

 4.    ICE SPEED           M/S          .0420      .0420   EXPONENTIAL

 5.    FRICTION ANGLE      DEG.     25.0000        .0000   DETERMINISTIC

 6.    COHESION            MPA          .0350      .0000   DETERMINISTIC

ENTER INDEX OF PARAMETER YOU WISH TO CHANGE (0=NONE)

LOWER BOUND CAN ALSO BE SET FOR SELECTED PARAMETER

0



PARTIAL ICE COVER LEVEL ICE PARAMETERS USED ARE :

INDEX   PARAMETER                              UNITS     VALUE


 1.     AVERAGE ICE PRESSURE                    MPA      0.30E+00

 2.     MEAN OF EXTREMAL PRESSURE COMPONENT     MPA      0.20E+00

 3.     S.D. OF EXTREMAL PRESSURE COMPONENT     MPA      0.15E+00
```

```
ENTER INDEX OF PARAMETER YOU WISH TO CHANGE (0=NONE)

0



PARTIAL ICE COVER MY FLOE PARAMETERS USED ARE AS FOLLOWS :


INDEX  PARAMETER          UNITS        MEAN   STD. DEV.  DISTRIBUTION


 1.    MY CONCENTRATION  TENTHS      .2000      .4000   BETA

 2.    FLOE VELOCITY      M/S        .0620      .0730   GAMMA

 3.    FLOE DIAMETER      KM         .1000      .1500   GAMMA

 4.    FLOE THICKNESS     M         3.9000     1.6000   GAMMA

 5.    ICE PRESSURE       MPA        .5000      .5000   EXPONENTIAL

 6.    MY RIDGE COVERAGE PERCENT 30.0000      .0000   DETERMINISTIC

 7.    MY RIDGE HEIGHT    M          .9000      .9000   EXPONENTIAL

 8.    MY RIDGE LENGTH    M       150.0000      .0000   DETERMINISTIC

 9.    FY ICE PRESSURE    MPA        .0500      .0500   NORMAL


ENTER INDEX OF PARAMETER YOU WISH TO CHANGE (0=NONE)

LOWER BOUND CAN ALSO BE SET FOR SELECTED PARAMETER

0
```

```
                    ****** P R O G R A M   I N P U T *****

                  INTERACTIVE PRE-PROCESSOR FOR PROBABILISTIC

                               ICE LOAD PROGRAM

                 DEVELOPED BY DET NORSKE VERITAS (CANADA) LTD.

                            RELEASED MARCH,1988




***RUN TITLE

DEMONSTRATION

***GEOGRAPHIC LOCATION, ICE ZONE, WATER DEPTH, DISTANCE OFFSHORE

BEAUFORT          PACK                      40.000                  50.000

***STRUCTURAL GEOMETRY

VERTICAL

CIRCULAR

*DIAMETER

     100.000

***SEASONS AND SEASON BOUNDARIES

*SEASON INDEX

           1

*DATE FOR BEGINNING OF PARTIAL ICE COVER

     173.000       18.100                  NORMAL

*DATE FOR BEGINNING OF OPEN WATER

     187.000       22.900                  NORMAL

***ICE PARAMETERS FOR PARTIAL ICE COVER CONDITIONS***

*INDEXES FOR PARTIAL ICE COVER LOADING CASES

1          1          1          0          0          0
```

```
*FY ICE THICKNESS

    1.500000

**FY RIDGE PARAMETERS

*COVERAGE (PERCENT)

 0.30000E+02    0.00000E+00    0.00000E+00   DETERMINISTIC

*HEIGHT (M)

 0.90000E+00    0.90000E+00    0.76000E+00   EXPONENTIAL

*LENGTH (M)

 0.15000E+03    0.00000E+00    0.00000E+00   DETERMINISTIC

*VELOCITY (M/S)

 0.42000E-01    0.42000E-01    0.00000E+00   EXPONENTIAL

*FRICTION ANGLE (RAD.)

 0.43633E+00    0.00000E+00    0.00000E+00   DETERMINISTIC

*COHESION (MPA)

 0.35000E-01    0.00000E+00    0.00000E+00   DETERMINISTIC

**LEVEL ICE PARAMETERS

*ICE PRESSURE :AVERAGE ,AND MEAN AND S.D. OF EXTREMAL COMPONENT

 0.300E+00   0.200E+00   0.150E+00

**MY FLOE PARAMETERS

*CONCENTRATION (TENTHS)

 0.20000E+00    0.40000E+00    0.00000E+00   BETA

*VELOCITY (M/S)

 0.62000E-01    0.73000E-01    0.00000E+00   GAMMA

*DIAMETER (KM)

 0.10000E+00    0.15000E+00    0.50000E+00   GAMMA

*THICKNESS (M)

 0.39000E+01    0.16000E+01    0.00000E+00   GAMMA

*PRESSURE (MPA)

 0.50000E+00    0.50000E+00    0.00000E+00   EXPONENTIAL

*RIDGE COVERAGE (PERCENT)
```

```
 0.30000E+02     0.00000E+00     0.00000E+00    DETERMINISTIC

*RIDGE HEIGHT (M)

 0.90000E+00     0.90000E+00     0.00000E+00    EXPONENTIAL

*RIDGE LENGTH (M)

 0.15000E+03     0.00000E+00     0.00000E+00    DETERMINISTIC

*FY ICE PRESSURE (MPA)

 0.50000E-01     0.50000E-01     0.00000E+00    NORMAL
```

3.4 Running MAIN

The purpose of MAIN is to use the input data file created by INPUT to perform the calculations and create the following files (see Chapter 2 for file organization):

i) A main output file which contains the important output parameters such as the force distribution parameters, the frequencies of occurrence of each scenario, the number of simulations in each case, etc.

ii) A dump output file (optional), which contains the ice parameters and resulting force in each Monte Carlo simulation for a given ice feature type in a given season. The user can also define a cut-off load value below which the simulation is not to be recorded in the dump file.

iii) A data base file which contains the detailed probabilistic description of the load for each scenario. This file is unformatted and can only be accessed through the output program OUTPUT.

If the version using IMSL (International Mathematical and Statistical Library) (1) routines is used, the following IMSL routines will be called by the program:

i) MDNOR calculates the cumulative probability for a standard normal density function
ii) MDGAM calculates the cumulative probability for a standard gamma density function
iii) MDBETA calculates the cumulative probability for a standard beta density function
iv) GGUBT generates a randon number from a basic 0-1 uniform density function
v) GGBTR generates a random number from a beta density function
vi) GGAMR generates a random number from a standard gamma density function

The user should therefore ensure that the IMSL is linked before running this version of MAIN.

Once the execution of MAIN is started, the user is asked to define the file names (only for INTFN = 1, see Section 2.1) and the run status (normal or re-start). Also, some run specific parameters are requested by the program as follows:

- The dump option status (see ii) above, active or inactive. If the dump option is active, the user would also be asked to define a minimum load value above which a certain simulation is to be recorded on the dump file.

- The tolerance: this is defined as the acceptable ratio of change of the mean force value due to one additional simulaton. The tolerance governs the number of simulations (lower tolerances would lead to larger numbers of simulations). The program stops when 5 consecutive values of the error are less than the prescribed tolerance. If the maximum number of simulations is reached before convergence, a warning message will be written to the output file.

- The bin width of the histogram in which the force values are to be grouped for further analysis. Since the maximum number of bins is 200, the user should choose the bin width such that the maximum expected load value is smaller than the upper bound of the 200th bin (i.e. maximum load $\leq$ 200 x bin width). If this condition is not satisfied, force values which fall outside of all bins will be ignored and a warning message will be written in the input file. If a large number of load values are lost such that the load distributions are poorly defined, the program will issue an error message and stop.

- Finally, a randomly chosen number is required as an initial seed for random number generation.

An example run is given here which uses the data file created by the INPUT run given in Section 3.3 as an input file with the re-start option off. A load cut-off value of zero is used for the dump file. The error tolerance is 0.025, the bin width is 10, and the initial seed is 1.D0. The example is displayed on the next few pages as follows:

i) Page 3-4-4 and 3-4-6 show the output file; and
ii) Pages 3-4-7 to 3-4-11 show the dump file.

The program also creates a data base file which cannot be displayed here because it is an unformatted file. The file contains probabilistic descriptions of the loads for different scenarios as shown in Table 3.4.1.

Table 3.4.1. Probabilistic Load Descriptors
Contained in the Data Base File
for Different Load Scenarios

Season	Scenario	Parameter		
		One Event	Monthly Extremes	Season Extremes
Partial Ice Cover	First-year ridges	✓		✓
	Level ice			✓
	Multi-year floes	✓		✓
	Icebergs	✓		✓
	Ice Islands	✓		✓
	Ice Island Fragments	✓		✓
Full Ice Cover	First-year ridges	✓		✓
	Level ice		✓	✓
	Multi-year floes	✓		✓
	Icebergs	✓		✓
	Ice Islands	✓		✓
	Ice Island fragments	✓		✓
Open Water	First-year floes	✓		✓
	Multi-year floes	✓		✓
	Icebergs	✓		✓
	Ice islands	✓		✓
	Ice islands fragments	✓		✓

```
                 ***** P R O G R A M   M A I N *****

         PROBABILISTIC ASSESSMENT OF YEAR-ROUND ICE LOADS ON

               FIXED STRUCTURES IN THE CANADIAN OFFSHORE

             DEVELOPED BY DET NORSKE VERITAS (CANADA) LTD.

                        RELEASED MARCH, 1988



RUN TITLE : DEMONSTRATION
=========



I/O FILE NAMES :
==============

  DATA BASE FILE :  DBTEST
  INPUT FILE     :  INTEST
  DUMP FILE      :  DUTEST



STATISTICAL PARAMETERS :
======================

  TOLERANCE FOR MEAN FORCE =   0.25E-01
  BIN WIDTH FOR FORCE PDF  =      10.00  MN
```

```
PARTIAL ICE COVER SEASON :
========================

 AVERAGE SEASON LENGTH =   20.  DAYS


 FIRST YEAR RIDGES :

   AVERAGE INTERACTION RATE        =   0.44E+03  PER SEASON
   NUMBER OF SIMULATIONS           =          33

   FORCE DISTRIBUTION PARAMETERS :

     FORCE                              MEAN (MN)          S.D. (MN)

     FOR ONE COLLISION                    25.25               25.94
     EXTREMAL                            115.00                 .05


 FIRST YEAR LEVEL ICE :


   SEASON EXTREME FORCE (MN) :
     MEAN       =     74.00  MN
     STD. DEV. =      23.64  MN
```

```
MULTIYEAR FLOE COLLISIONS :

   AVERAGE COLLISION RATE          =    0.16E+01  PER SEASON

   NUMBER OF SIMULATIONS           =          42


   FORCE DISTRIBUTION PARAMETERS :


      FORCE                              MEAN (MN)            S.D. (MN)


      FOR ONE COLLISION                     56.66                56.55

      EXTREMAL                              62.34                66.38
```

```
                       ***** P R O G R A M   M A I N *****

           PROBABILISTIC ASSESSMENT OF YEAR-ROUND ICE LOADS ON

                  FIXED STRUCTURES IN THE CANADIAN OFFSHORE

              DEVELOPED BY DET NORSKE VERITAS (CANADA) LTD.

                          RELEASED MARCH, 1988




PARTIAL ICE COV

FIRST YEAR RIDGES


HEIGHT       COHESION     FRC AGL      FORCE

M            MPA          RAD.         MN


.316E+01     .350E-01     .436E+00     .672E+02

.119E+01     .350E-01     .436E+00     .915E+01

.961E+00     .350E-01     .436E+00     .594E+01

.218E+01     .350E-01     .436E+00     .314E+02

.247E+01     .350E-01     .436E+00     .405E+02

.991E+00     .350E-01     .436E+00     .633E+01

.767E+00     .350E-01     .436E+00     .377E+01

.292E+01     .350E-01     .436E+00     .571E+02

.153E+01     .350E-01     .436E+00     .153E+02

.107E+01     .350E-01     .436E+00     .736E+01

.317E+01     .350E-01     .436E+00     .675E+02
```

```
 .402E+01    .350E-01    .436E+00    .111E+03

 .893E+00    .350E-01    .436E+00    .513E+01

 .114E+01    .350E-01    .436E+00    .839E+01

 .886E+00    .350E-01    .436E+00    .504E+01

 .125E+01    .350E-01    .436E+00    .101E+02

 .204E+01    .350E-01    .436E+00    .275E+02

 .163E+01    .350E-01    .436E+00    .173E+02

 .143E+01    .350E-01    .436E+00    .133E+02

 .336E+01    .350E-01    .436E+00    .762E+02

 .878E+00    .350E-01    .436E+00    .495E+01

 .299E+01    .350E-01    .436E+00    .600E+02

 .137E+01    .350E-01    .436E+00    .122E+02

 .254E+01    .350E-01    .436E+00    .428E+02

 .203E+01    .350E-01    .436E+00    .270E+02

 .918E+00    .350E-01    .436E+00    .542E+01

 .118E+01    .350E-01    .436E+00    .902E+01

 .832E+00    .350E-01    .436E+00    .444E+01

 .130E+01    .350E-01    .436E+00    .109E+02

 .186E+01    .350E-01    .436E+00    .227E+02

 .126E+01    .350E-01    .436E+00    .103E+02

 .955E+00    .350E-01    .436E+00    .587E+01

 .223E+01    .350E-01    .436E+00    .327E+02



PART ICE COVER

MULTIYEAR FLOES


FY THK    YM THK    FLO DIAM  VELOCITY  ECCEN.    APR AGLE  FY PRESS  MY
 PRESS  FORCE

M         M         KM        M/S       M         RAD.      MPA       MP
```

```
.150E+01  .585E+01  .975E+00  .222E+00  .490E+03  .000E+00  .136E-01  .2
03E+00  .586E+02
.150E+01  .195E+01  .975E+00  .740E-01  .500E+03  .000E+00  .677E-02  .3
16E-01  .616E+01
.150E+01  .585E+01  .975E+00  .740E-01  .323E+03  .000E+00  .932E-02  .1
16E+00  .247E+02
.150E+01  .214E+01  .975E+00  .222E+00  .359E+03  .000E+00  .269E-02  .1
47E+00  .160E+02
.150E+01  .585E+01  .975E+00  .740E-01  .316E+03  .000E+00  .360E-01  .8
43E-01  .493E+02
.150E+01  .647E+01  .975E+00  .222E+00  .147E+03  .000E+00  .148E-01  .1
04E+01  .169E+03
.150E+01  .195E+01  .975E+00  .740E-01  .186E+03  .000E+00  .137E-01  .2
31E+00  .239E+02
.150E+01  .195E+01  .975E+00  .222E+00  .449E+03  .000E+00  .642E-02  .1
22E+01  .578E+02
.150E+01  .195E+01  .975E+00  .740E-01  .444E+02  .000E+00  .517E-01  .1
94E+00  .378E+02
.150E+01  .585E+01  .975E+00  .740E-01  .105E+03  .000E+00  .170E-01  .6
82E+00  .668E+02
.150E+01  .585E+01  .975E+00  .222E+00  .157E+03  .000E+00  .439E-02  .9
57E+00  .138E+03
.150E+01  .857E+01  .975E+00  .444E+00  .328E+03  .000E+00  .222E-01  .1
64E+00  .108E+03
.150E+01  .195E+01  .975E+00  .740E-01  .336E+03  .000E+00  .468E-02  .2
31E+00  .128E+02
.150E+01  .195E+01  .195E+01  .444E+00  .434E+03  .000E+00  .214E-01  .1
65E+00  .321E+02
```

```
.150E+01  .880E+01  .975E+00  .740E-01  .487E+03  .000E+00  .333E-01  .9
35E+00  .126E+03
.150E+01  .732E+01  .975E+00  .740E-01  .439E+03  .000E+00  .370E-02  .3
60E-01  .123E+02
.150E+01  .195E+01  .975E+00  .444E+00  .448E+03  .000E+00  .510E-02  .3
49E+00  .393E+02
.150E+01  .117E+02  .975E+00  .740E-01  .350E+03  .000E+00  .549E-02  .2
44E-01  .160E+02
.150E+01  .585E+01  .975E+00  .222E+00  .792E+02  .000E+00  .116E-01  .1
71E+01  .207E+03
.150E+01  .272E+01  .975E+00  .740E-01  .190E+03  .000E+00  .344E-01  .8
05E+00  .648E+02
.150E+01  .195E+01  .975E+00  .444E+00  .231E+03  .000E+00  .753E-01  .2
00E+00  .391E+02
.150E+01  .224E+01  .975E+00  .740E-01  .413E+03  .000E+00  .207E-02  .4
26E+00  .161E+02
.150E+01  .585E+01  .975E+00  .740E-01  .268E+03  .000E+00  .198E-01  .2
21E+00  .444E+02
.150E+01  .584E+01  .975E+00  .740E-01  .124E+03  .000E+00  .342E-02  .1
33E+01  .832E+02
.150E+01  .195E+01  .975E+00  .444E+00  .494E+03  .000E+00  .665E-02  .5
52E+00  .537E+02
.150E+01  .291E+01  .975E+00  .740E-01  .175E+03  .000E+00  .177E-02  .6
56E-01  .690E+01
.150E+01  .585E+01  .975E+00  .444E+00  .273E+02  .000E+00  .230E-01  .1
26E+00  .683E+02
.150E+01  .195E+01  .975E+00  .444E+00  .246E+03  .000E+00  .719E-02  .4
18E+00  .457E+02
.150E+01  .585E+01  .975E+00  .740E-01  .424E+03  .000E+00  .935E-02  .2
75E+00  .364E+02
```

```
.150E+01  .195E+01  .975E+00  .740E-01  .407E+03  .000E+00  .832E-02  .7
52E-01  .134E+02
.150E+01  .585E+01  .975E+00  .444E+00  .259E+03  .000E+00  .176E-01  .8
29E+00  .205E+03
.150E+01  .117E+02  .975E+00  .222E+00  .140E+03  .000E+00  .628E-03  .7
29E+00  .225E+03
.150E+01  .346E+01  .975E+00  .740E-01  .233E+03  .000E+00  .101E-01  .3
74E+00  .298E+02
.150E+01  .583E+01  .975E+00  .740E-01  .390E+03  .000E+00  .242E-03  .4
85E-02  .199E+01
.150E+01  .393E+01  .975E+00  .740E-01  .337E+03  .000E+00  .252E-02  .7
07E+00  .376E+02
.150E+01  .195E+01  .975E+00  .222E+00  .290E+03  .000E+00  .941E-02  .6
47E+00  .424E+02
.150E+01  .585E+01  .975E+00  .740E-01  .266E+02  .000E+00  .866E-03  .8
42E-02  .337E+01
.150E+01  .195E+01  .975E+00  .740E-01  .372E+03  .000E+00  .374E-02  .7
23E-01  .768E+01
.150E+01  .307E+01  .195E+01  .740E-01  .311E+03  .000E+00  .174E-01  .7
23E+00  .802E+02
.150E+01  .195E+01  .975E+00  .222E+00  .428E+03  .000E+00  .107E-01  .9
20E-01  .179E+02
.150E+01  .585E+01  .975E+00  .740E-01  .217E+03  .000E+00  .681E-02  .5
89E-01  .166E+02
.150E+01  .665E+01  .975E+00  .740E-01  .470E+02  .000E+00  .153E-01  .1
80E+00  .390E+02
```

3.5 Running OUTPUT

The purpose of OUTPUT is to process the output of MAIN which is given on an unformatted data base file as discussed in Section 2.4 and Section 3.4. The data base contains the run title and the appropriate probabilistic description for the load in each scenario as detailed in Table 3.4.1. On the data base, all forces are described by the cumulative density function. OUTPUT performs the following functions:

i) Extract the probabilistic description for the load and/or extreme load during any of the scenarios available on the data base.

ii) Compute the extremal load cumulative distribution function from the scenario extremes for any combination(s) of scenarios.

iii) Convert the probabilistic load description, if necessary, to present it in any of the following formats:

- Cumulative density function (CDF)
- Probability of exceedance plot (POE)
- Probability density function (PDF)
- Return period plot (REP)

The output of OUTPUT is in the form of graphics oriented, x-y arrays with the x representing the force values and the y representing the requested probabilistic description. Before each array, the run title, output format, curve description and axes labels are given. The program does not plot the results. If plotted output is required, the user should write an interface program to plot the results in this output file. It is noted that if the return period is selected as an output format, the last y value on the curve could be ∞ (due to the definition of the return period). A value of 10E10 will be given to denote that the curve is asymptotic to the corresponding force value.

An example is given here, where the data base created by MAIN (see example of Section 3.4) is processed. The example is run in the normal mode (i.e. no data retrieval). This program is interactive and self explanatory. The example is given in this section as follows:

i) Pages 3-5-3 to 3-5-5 show the back-up file created by OUTPUT. This file gives all screen prompts and user responses.

ii) Pages 3-5-6 to 3-5-16 give a print of the output file resulting from this run.

It is worth noting that OUTPUT can be re-run with the same data base file to produce other results, or the same results in different formats.

```
                    ****  P R O G R A M   O U T P U T ****


                  INTERACTIVE POST-PROCESSOR FOR PROBABILISTIC

                               ICE LOAD PROGRAM

                  DEVELOPED BY DET NORSKE VERITAS (CANADD) LTD.

                             RELEASED MARCH, 1988


ENTER NAME OF DATA BASE FILE (MAX.15 CHARACTERS)

DBTEST


 ENTER NAME OF FILE FOR PRINTED OUTPUT (MAX. 15 CHARACTERS)

OUTTEST


 SELECT PROCESSING OPTION


   1 = PROCESS EACH SINGLE SCENARIO ON DATA BASE

   2 = COMBINE ALL SCENARIOS ON DATA BASE

   3 = SELECT ONE SCENARIO

   4 = COMBINE SCENARIOS ONE BY ONE

   5 = COMBINE ALL SCENARIOS FOR PARTIAL ICE COVER

   6 = COMBINE FIRST YEAR RIDGES FOR ALL SEASONS

   7 = COMBINE FIRST YEAR LEVEL ICE FOR ALL SEASONS

   8 = COMBINE MULTI YEAR FLOES FOR ALL SEASONS


 ENTER OPTION 1 TO  8 OR 0 TO STOP

1


 AVAILABLE FORMATS FOR OUTPUT
```

```
INDEX FORMAT                                              STATUS

1.    CUMULATIVE PROBABILITY                    (CDF)  NOT PROCESSED
2.    PROBABILITY DENSITY                       (PDF)  NOT PROCESSED
3.    PROBABILITY OF EXCEEDANCE                 (POE)  NOT PROCESSED
4.    RETURN PERIOD                             (RPE)  NOT PROCESSED

ENTER INDEX TO CHANGE OR 0 TO EXIT
1

AVAILABLE FORMATS FOR OUTPUT

INDEX FORMAT                                              STATUS

1.    CUMULATIVE PROBABILITY                    (CDF)  PROCESSED
2.    PROBABILITY DENSITY                       (PDF)  NOT PROCESSED
3.    PROBABILITY OF EXCEEDANCE                 (POE)  NOT PROCESSED
4.    RETURN PERIOD                             (RPE)  NOT PROCESSED

ENTER INDEX TO CHANGE OR 0 TO EXIT
4

AVAILABLE FORMATS FOR OUTPUT

INDEX FORMAT                                              STATUS

1.    CUMULATIVE PROBABILITY                    (CDF)  PROCESSED
2.    PROBABILITY DENSITY                       (PDF)  NOT PROCESSED
3.    PROBABILITY OF EXCEEDANCE                 (POE)  NOT PROCESSED
4.    RETURN PERIOD                             (RPE)  PROCESSED
```

```
 ENTER INDEX TO CHANGE OR 0 TO EXIT
0


 DEFINE PARAMETER


 INDEX  FORMAT        SCENARIO               PARAMETER      COMPONENT


  1. CDF/RPE         ALL SCENARIOS          ONE INTERACTION HORIZONTAL

  2. CDF/RPE         ALL SCENARIOS          SEASON EXTREMES HORIZONTAL

  3. CDF/RPE         PARAMETER 1. AND 2.


 ENTER INDEX OF PARAMETER FOR OUTPUT
3


 SELECT PROCESSING OPTION


  1 = PROCESS EACH SINGLE SCENARIO ON DATA BASE

  2 = COMBINE ALL SCENARIOS ON DATA BASE

  3 = SELECT ONE SCENARIO

  4 = COMBINE SCENARIOS ONE BY ONE

  5 = COMBINE ALL SCENARIOS FOR PARTIAL ICE COVER

  6 = COMBINE FIRST YEAR RIDGES FOR ALL SEASONS

  7 = COMBINE FIRST YEAR LEVEL ICE FOR ALL SEASONS

  8 = COMBINE MULTI YEAR FLOES FOR ALL SEASONS


 ENTER OPTION 1 TO  8 OR 0 TO STOP
0
```

```
*PROGRAM

                              **** P R O G R A M   O U T P U T ****

                         INTERACTIVE POST-PROCESSOR FOR PROBABILISTIC

                                      ICE LOAD PROGRAM

                         DEVELOPED BY DET NORSKE VERITAS (CANADD) LTD.

                                   RELEASED MARCH, 1986

 *DRAWING NUMBER

           1

 *TITLE

 VERTICAL

 *FORMAT

 CDF

 *CURVE

 *PARAMETER

  PARTIAL ICE COVER //FIRST YEAR RIDGES

 *X LABEL

 FORCE

 *Y LABEL

 CDF

 *CURVE

  6.637920E+01 ,  6.637920E+01

  2.517864E-01 ,  2.517864E-01

  3.392648E-01 ,  3.392648E-01

  3.794057E-01 ,  3.794057E-01

  4.925179E-01 ,  4.925179E-01

  5.717093E-01 ,  5.717093E-01

  6.393523E-01 ,  6.393523E-01
  7.149986E-01 ,  7.149986E-01
  7.149986E-01 ,  7.149986E-01
  7.703388E-01 ,  7.703388E-01
  7.703388E-01 ,  7.703388E-01
  7.995951E-01 ,  7.995951E-01
  7.995951E-01 ,  7.995951E-01
 *CURVE
 *PARAMETER
  PARTIAL ICE COVER //FIRST YEAR RIDGES
 *X LABEL
 FORCE
 *Y LABEL
 CDF
 *CURVE
  6.637920E+01 ,  6.637920E+01
  2.517864E-01 ,  2.517864E-01
  3.392648E-01 ,  3.392648E-01
  3.794057E-01 ,  3.794057E-01
  4.925179E-01 ,  4.925179E-01
  5.717093E-01 ,  5.717093E-01
  6.393523E-01 ,  6.393523E-01
  7.149986E-01 ,  7.149986E-01
  7.149986E-01 ,  7.149986E-01
  7.703388E-01 ,  7.703388E-01
  7.703388E-01 ,  7.703388E-01
  7.995951E-01 ,  7.995951E-01
  7.995951E-01 ,  7.995951E-01
*DRAWING NUMBER
          2
*TITLE
```

```
VERTICAL
*FORMAT
RFE
*CURVE
*PARAMETER
 PARTIAL ICE COVER //FIRST YEAR RIDGES
*X LABEL
FORCE
*Y LABEL
RFE
*CURVE
 6.637920E+01 ,  1.000000E+10
 2.517864E-01 ,  1.336517
 3.392648E-01 ,  1.513466
 3.794057E-01 ,  1.611359
 4.925179E-01 ,  1.970513
 5.717093E-01 ,  2.334863
 6.393523E-01 ,  2.772789
 7.149986E-01 ,  3.508754
 7.149986E-01 ,  3.508754
 7.703388E-01 ,  4.354241
 7.703388E-01 ,  4.354241
 7.995951E-01 ,  4.989897
 7.995951E-01 ,  4.989897
*CURVE
*PARAMETER
 PARTIAL ICE COVER //FIRST YEAR RIDGES
*X LABEL
FORCE
*Y LABEL
```

```
*CURVE
 6.637920E+01 ,  1.000000E+10
 2.517864E-01 ,  1.336517
 3.392648E-01 ,  1.513466
 3.794057E-01 ,  1.611359
 4.925179E-01 ,  1.970513
 5.717093E-01 ,  2.334863
 6.393523E-01 ,  2.772789
 7.149986E-01 ,  3.508754
 7.149986E-01 ,  3.508754
 7.703368E-01 ,  4.354241
 7.703368E-01 ,  4.354241
 7.995951E-01 ,  4.989897
 7.995951E-01 ,  4.989897
*DRAWING NUMBER
          3
*TITLE
VERTICAL
*FORMAT
CDF
*CURVE
*PARAMETER
 PARTIAL ICE COVER //FIRST YEAR LEVEL ICE
*X LABEL
FORCE
*Y LABEL
CDF
*CURVE
 6.637920E+01 ,  6.637920E+01
 2.517864E-01 ,  2.517864E-01
 3.392648E-01 ,  3.392648E-01
 3.794057E-01 ,  3.794057E-01
 4.925179E-01 ,  4.925179E-01
 5.717093E-01 .  5.717093E-01
 6.393523E-01 .  6.393523E-01
 7.149986E-01 ,  7.149986E-01
 7.149986E-01 ,  7.149986E-01
 7.703388E-01 ,  7.703388E-01
 7.703388E-01 ,  7.703388E-01
 7.995951E-01 .  7.995951E-01
 7.995951E-01 ,  7.995951E-01
 8.299624E-01 ,  8.299624E-01
*DRAWING NUMBER
          4
*TITLE
VERTICAL
*FORMAT
RPE
*CURVE
*PARAMETER
 PARTIAL ICE COVER //FIRST YEAR LEVEL ICE
*X LABEL
FORCE
*Y LABEL
RPE
*CURVE
 6.637920E+01 ,  1.000000E+10
 2.517864E-01 ,  1.336517
 3.392648E-01 ,  1.513466
 3.794057E-01 ,  1.611359
 4.925179E-01 ,  1.970513
 5.717093E-01 ,  2.334863
 6.393523E-01 ,  2.772789
 7.149986E-01 ,  3.508754
 7.149986E-01 ,  3.508754
 7.703388E-01 ,  4.354241
 7.703388E-01 ,  4.354241
 7.995951E-01 ,  4.989897
 7.995951E-01 ,  4.989897
 8.299624E-01 ,  5.881053
*DRAWING NUMBER
         5
*TITLE
VERTICAL
*FORMAT
CDF
*CURVE
*PARAMETER
 PARTIAL ICE COVER //MULTI YEAR FLOES
*X LABEL
FORCE
*Y LABEL
CDF
*CURVE
 6.637920E+01 ,  6.637920E+01
 2.517864E-01 ,  2.517864E-01
 3.392648E-01 ,  3.392648E-01
 3.794057E-01 ,  3.794057E-01
 4.925179E-01 ,  4.925179E-01
 5.717093E-01 .  5.717093E-01
 6.393523E-01 ,  6.393523E-01
 7.149986E-01 ,  7.149986E-01
 7.149986E-01 ,  7.149986E-01
 7.703388E-01 ,  7.703388E-01
 7.703388E-01 ,  7.703388E-01
 7.995951E-01 ,  7.995951E-01
 7.995951E-01 ,  7.995951E-01
 8.299624E-01 ,  8.299624E-01
 8.614831E-01 .  8.614831E-01
 8.614831E-01 ,  8.614831E-01
 8.614831E-01 ,  8.614831E-01
 8.942008E-01 ,  8.942008E-01
 8.942008E-01 .  8.942008E-01
 8.942008E-01 ,  8.942008E-01
 8.942008E-01 ,  8.942008E-01
 9.634112E-01 ,  9.634112E-01
 9.634112E-01 ,  9.634112E-01
 1.000000 ,  1.000000
*CURVE
*PARAMETER
 PARTIAL ICE COVER //MULTI YEAR FLOES
*X LABEL
FORCE
*Y LABEL
CDF
*CURVE
 6.637920E+01 ,  6.637920E+01
 2.517864E-01 ,  2.517864E-01
 3.392648E-01 ,  3.392648E-01
```

```
3.794057E-01 ,  3.794057E-01

4.925179E-01 ,  4.925179E-01

5.717093E-01 ,  5.717093E-01

6.393523E-01 ,  6.393523E-01

7.149986E-01 ,  7.149986E-01

7.149986E-01 ,  7.149986E-01

7.703388E-01 ,  7.703388E-01

7.703388E-01 ,  7.703388E-01

7.995951E-01 ,  7.995951E-01

7.995951E-01 ,  7.995951E-01

8.299624E-01 ,  8.299624E-01

8.614831E-01 ,  8.614831E-01

8.614831E-01 ,  8.614831E-01

8.614831E-01 ,  8.614831E-01

8.942008E-01 ,  8.942008E-01

8.942008E-01 ,  8.942008E-01

8.942008E-01 ,  8.942008E-01

8.942008E-01 ,  8.942008E-01

9.634112E-01 ,  9.634112E-01

9.634112E-01 ,  9.634112E-01

1.000000 ,  1.000000

*DRAWING NUMBER

          6

*TITLE

VERTICAL

*FORMAT

RPE

*CURVE

*PARAMETER

 PARTIAL ICE COVER //MULTI YEAR FLOES
```

```
*X LABEL
FORCE
*Y LABEL
RPE
*CURVE
 6.637920E+01 ,  1.000000E+10
 2.517864E-01 ,  1.336517
 3.392648E-01 ,  1.513466
 3.794057E-01 ,  1.611359
 4.925179E-01 ,  1.970513
 5.717093E-01 ,  2.334863
 6.393523E-01 ,  2.772789
 7.149986E-01 ,  3.508754
 7.149986E-01 ,  3.508754
 7.703388E-01 ,  4.354241
 7.703388E-01 ,  4.354241
 7.995951E-01 ,  4.989897
 7.995951E-01 ,  4.989897
 8.299624E-01 ,  5.881053
 8.614831E-01 ,  7.219333
 8.614831E-01 ,  7.219333
 8.614831E-01 ,  7.219333
 8.942008E-01 ,  9.451867
 8.942008E-01 ,  9.451867
 8.942008E-01 ,  9.451867
 8.942008E-01 ,  9.451867
 9.634112E-01 ,  2.733076E+01
 9.634112E-01 ,  2.733076E+01
 1.000000 ,  1.000000E+10
*CURVE
```

```
*PARAMETER
 PARTIAL ICE COVER //MULTI YEAR FLOES
*X LABEL
FORCE
*Y LABEL
RPE
*CURVE
 6.637920E+01 ,  1.000000E+10
 2.517864E-01 ,  1.336517
 3.392648E-01 ,  1.513466
 3.794057E-01 ,  1.611359
 4.925179E-01 ,  1.970513
 5.717093E-01 ,  2.334863
 6.393523E-01 ,  2.772789
 7.149986E-01 ,  3.508754
 7.149986E-01 ,  3.508754
 7.703388E-01 ,  4.354241
 7.703388E-01 ,  4.354241
 7.995951E-01 ,  4.989897
 7.995951E-01 ,  4.989897
 8.299624E-01 ,  5.881053
 8.614831E-01 ,  7.219333
 8.614831E-01 ,  7.219333
 8.614831E-01 ,  7.219333
 8.942008E-01 ,  9.451867
 8.942008E-01 ,  9.451867
 8.942008E-01 ,  9.451867
 8.942008E-01 ,  9.451867
 9.634112E-01 ,  2.733076E+01
 9.634112E-01 ,  2.733076E+01
 1.000000 ,  1.000000E+10
```

3.6 Running LOCAL

LOCAL is a self-contained interactive program which accepts screen input and calculates the local ice pressures on a panel of the structure with user defined dimensions. The program is fully interactive and self explanatory. The user begins by defining file names and some run statistical parameters (similar to those in MAIN). The dimensions of the design panel and the relevant structural characteristics are then defined, followed by the ice parameters for a given loading scenario. The program calculates the cumulative density function of the local ice pressure on the given panel.

The program then gives the option of considering another loading scenario on the same panel. If selected, this option repeats the definition of ice parameters using those for the previous scenario as default, then calculates the CDF of the local pressure from the new scenario. It also calculates the CDF of the local pressures for all previous scenarios combined. A sequence of three scenarios for example would give output for scenario 1, scenario 2, scenario 1 and 2 combined, scenario 3 and scenarios 1, 2 and 3 combined.

LOCAL generates 2 files. The first is a result summary file giving an echo of the input data and the calculated distribuiton means and standard deviations. The second is a distribution file which gives graphics oriented printed outputs of the CDF's of the local pressure distributions calculated.

An example run is given in the following for a 2 scenario case using a bin width of 0.5 MPa, a tolerance of .001 and an initial seed of 1.DO. Both scenarios represent ice sheet interactions:

i) Pages 3-6-2 to 3-6-4 gives the summary output file with an echo of the input data.

ii) Pages 3-6-5 to 3-6-8 gives the corresponding distribution file.

```
RUN TITLE : TEST
=========



DESIGN PANLE DIMENSIONS :
=======================



INDEX    PARAMETER                                  UNITS     VALUE


 1.      HEIGHT FROM SEABOTTOM                      M         0.40E+02
 2.      WIDTH                                      M         0.50E+01
 3.      DEPTH                                      M         0.10E+01
 4.      STRUCTURE PERIMETER                        M         0.40E+03



SCENARIO NUMBER  1
==================


PRESSURE HISTORY INPUT PARAMETERS :


INDEX    PARAMETER                                  UNITS     VALUE


 1.      DISCRETIZED SAMPLING RATE                  /MINUTE   0.50E+01
```

```
  2.      MEAN VALUE                                   MPA       0.40E+01

  3.      STANDARD DEVIATION                           MPA       0.15E+01

  4.      ASPECT RATIO FOR MEASUREMENT                 M**2      0.30E+01


ICE CONTACT INPUT PARAMETERS :


INDEX  PARAMETER          UNITS       MEAN   STD. DEV.  DISTRIBUTION


  1.    MEAN OCCURRENCE RA/YEAR   10.0000        .0000  DETERMINISTIC

  2.    DURATION          MINUTE  60.0000        .0000  DETERMINISTIC

  3.    CONTACT WIDTH     M      100.0000        .0000  DETERMINISTIC

  4.    CONTACT DEPTH     M        2.0000       1.0000  NORMAL

  5.    HEIGHT OF CONTACT M       40.0000        .0000  DETERMINISTIC


AVERAGE CONTACT TIME =  0.246E+03


DIST. PARAMETERS FOR INDIVIDUAL SCENARIO EXTREMAL PRESSURE :


MEAN                 =     0.8705E+01   MPA

STANDARD DEVIATION =       0.5679E+00   MPA




SCENARIO NUMBER  2
=================


PRESSURE HISTORY INPUT PARAMETERS :


INDEX    PARAMETER                                     UNITS     VALUE
```

```
 1.      DISCRETIZED SAMPLING RATE                  /MINUTE   0.10E+02
 2.      MEAN VALUE                                 MPA       0.60E+01
 3.      STANDARD DEVIATION                         MPA       0.15E+01
 4.      ASPECT RATIO FOR MEASUREMENT               M**2      0.30E+01


ICE CONTACT INPUT PARAMETERS :


INDEX  PARAMETER          UNITS       MEAN    STD. DEV.  DISTRIBUTION


 1.    MEAN OCCURRENCE RA/YEAR   30.0000       .0000   DETERMINISTIC
 2.    DURATION          MINUTE   5.0000       .0000   DETERMINISTIC
 3.    CONTACT WIDTH     M       20.0000     20.0000   EXPONENTIAL
 4.    CONTACT DEPTH     M        4.0000      2.0000   NORMAL
 5.    HEIGHT OF CONTACT M       40.0000       .0000   DETERMINISTIC

AVERAGE CONTACT TIME =  0.122E+02

DIST. PARAMETERS FOR INDIVIDUAL SCENARIO EXTREMAL PRESSURE :

MEAN                 =      0.9843E+01  MPA
STANDARD DEVIATION =      0.5778E+00  MPA

DIST. PARAMETERS FOR EXTREMAL PRESSURE OF ALL PREVIOUS
 SCENARIOS COMBINED :

MEAN                 =      0.9854E+01  MPA
STANDARD DEVIATION =      0.5622E+00  MPA
```

```
RUN TITLE : TEST
=========
*DRAWING NUMBER
             1
*TITLE
TEST
*FORMAT
CDF
*PARAMETER
SCENARIO  1   //EXTREME
*X LABEL
PRESSURE (MPA)
*Y LABEL
CUMULATIVE PROBABILITY
*CURVE
  .000000E+00  .000000E+00
  5.000000E-01  .000000E+00
  1.000000  .000000E+00
  1.500000  .000000E+00
  2.000000  .000000E+00
  2.500000  .000000E+00
  3.000000  .000000E+00
  3.500000  .000000E+00
  4.000000  .000000E+00
  4.500000  .000000E+00
  5.000000  .000000E+00
  5.500000  .000000E+00

  6.000000  .000000E+00

  6.500000  .000000E+00

  7.000000  .000000E+00

  7.500000  1.369863E-02

  8.000000  1.095890E-01

  8.500000  3.287671E-01

  9.000000  7.123288E-01

  9.500000  8.904110E-01

  1.000000E+01  9.863014E-01

  1.050000E+01  1.000000

*GRAPHIC NUMBER

          2

*TITLE

TBD

*FORMAT

C[illegible]

*PARAMETER

SCENARIO  2   (EXTREME

*X LABEL

PRESSURE (MPA)

*Y LABEL

CUMULATIVE PROBABILITY

*CURVE

  .000000E+00  .000000E+00

  5.000000E-01  .000000E+00

  1.000000  .000000E+00

  1.500000  .000000E+00

  2.000000  .000000E+00

  2.500000  .000000E+00
```

```
   3.000000  .000000E+00
   3.500000  .000000E+00
   4.000000  .000000E+00
   4.500000  .000000E+00
   5.000000  .000000E+00
   5.500000  .000000E+00
   6.000000  .000000E+00
   6.500000  .000000E+00
   7.000000  .000000E+00
   7.500000  .000000E+00
   8.000000  .000000E+00
   8.500000  .000000E+00
   9.000000  3.448276E-02
   9.500000  3.103448E-01
   1.000000E+01  6.724138E-01
   1.050000E+01  8.793103E-01
   1.100000E+01  9.482759E-01
   1.150000E+01  1.000000
*DRAWING NUMBER
          3
*TITLE
TEST
*FORMAT
CDF
*PARAMETER
SCENARIOS 1 : 2 COMBINED     //EXTREME
*X LABEL
PRESSURE (MPA)
*Y LABEL
CUMULATIVE PROBABILITY
```

```
      [illegible]  .000000E+00
        5.000001E-01  .000000E+00
1.000000  .000000E+00
1.500000  .000000E+00
2.000000  .000000E+00
2.500000  .000000E+00
3.000000  .000000E+00
3.500000  .000000E+00
4.000000  .000000E+00
4.500000  .000000E+00
5.000000  .000000E+00
5.500000  .000000E+00
6.000000  .000000E+00
6.500000  .000000E+00
7.000000  .000000E+00
7.500000  .000000E+00
8.000000  .000000E+00
8.500000  .000000E+00
9.000000  2.456306E-02
9.500000  2.763344E-01
1.000000E+01  6.632026E-01
1.050000E+01  8.793103E-01
1.100000E+01  9.482759E-01
1.150000E+01  1.000000
```

3.7 The Re-start and Data Retrieval Options for Global Load Package

The example given in Sections 3.3 through 3.5 considered only full ice cover scenarios (first-year ridges, level ice and multi-year floes) for a vertical circular structure in the pack zone of the Canadian Beaufort Sea. This section will demonstrate the steps needed to add open water multi-year floes to the data base, taking advantage of the data retrieval option in INPUT and the re-start option in MAIN, in order to minimize the computer and operater time required. It is emphasized that if a run is performed in segments in the manner shown here, the sequence of running the different scenarios must be the same as the order given in Table 1.4.1. The steps are as follows:

1. Edit the back-up file created by the previous run (Sec. 3.3) and locate the first response from the top which is not valid for the present combination of scenarios. This is, in this case, the season selection which includes a negative response to the open water season. Now, delete the bottom portion of the file starting with and including this response.

2. If INTFN = 1 (see Section 2.1), then move to step 3. If INTFN = 0, you need to ensure that the back-up file is attached to unit NUBU (i.e. the input back-up file as discussed in Section 2.3 and 2.4). This will be automatically the case if the back-up file was created by a run which did not use the retrieval option the present example). If the retrieval option were used in the run which produced the back-up file, the latter would be on unit NUSCBU, and should be reassigned to unit NUBU.

3. Run INPUT with the data retrieval option. No messages will appear on the screen until the end of the back-up file is reached, and then the program will switch back to interactive mode and you can continue to give the appropriate responses. The resulting output data file is given on pages 3-7-4 to 3-7-7. A new back-up file is also created by this run, which contains complete back-up information corresponding to the updated run. This is printed on pages 3-7-8 to 3-7-14.

4. If INTFN = 1 (see Section 2.1), move to step 5. If INTFN = 0, you must ensure that the data base file from the previous run is attached to unit NUDB (i.e. the input data base file as discussed in Section 2.3 and 2.4). This will be automatically the case if the data base file was created by a run which did not use the re-start option (the present example). If the re-start option was used in the run which produced the data base file, the latter would be on unit NUSCDB, and should be reassigned to unit NUDB.

5. Run MAIN in the re-start mode using the data base file created from the previous MAIN run (see Section 3.5), the data file created in Step 3 above as input and a seed of 2.D0. This run will produce a new output file (pages 3-7-15 to 3-7-18). If the dump option is active, the dump file will contain results for only the added scenario (summer multi-year floes). It is therefore important to save the dump file created by the original MAIN run (see Section 3.4). The new dump file is given in pages 3-7-19 and 3-7-22. The run also produces a new data base file which contains the results for all winter scenarios considered in the original run as well as the newly added summer multi-year floe scenario.

6. Run OUTPUT using the new data base file to process the required output.

NOTE; For INTFN = 0, the back-up file created in Step 3 and the data base file created in Step 5 above will be on units NUSCBU and NUSCDB respectively (see also Table 2.3.1 and Figure 2.4.1). If INTFN = 1, the user need not be concerned with unit numbers since all files are defined by names entered interactively by the user.

The use of the data retrieval from back-up file for OUTPUT was not needed for the above example. However, the steps for implementing this option in OUTPUT are identical to those for INPUT. The only restriction is that the data base file must be the same for both the original run and the retrieval run.

The data retrieval and re-start option can also be used for retrieving data for any run of either of the three programs that is abnormally aborted provided that the system allows for the associated files to be created and properly closed. The procedure for any such retrieval operation is identical to the procedure followed in the above example.

```
                    ****** P R O G R A M   I N P U T *****

                  INTERACTIVE PRE-PROCESSOR FOR PROBABILISTIC

                              ICE LOAD PROGRAM

                 DEVELOPED BY DET NORSKE VERITAS (CANADA) LTD.

                           RELEASED MARCH,1988




***RUN TITLE

DEMONSTARTION

***GEOGRAPHIC LOCATION, ICE ZONE, WATER DEPTH, DISTANCE OFFSHORE

BEAUFORT            PACK                     40.000                50.000

***STRUCTURAL GEOMETRY

VERTICAL

CIRCULAR

*DIAMETER

     100.000

***SEASONS AND SEASON BOUNDARIES

*SEASON INDEX

           5

*DATE FOR BEGINNING OF PARTIAL ICE COVER

     173.000         18.100                  NORMAL

*DATE FOR BEGINNING OF OPEN WATER

     187.000         22.900                  NORMAL

*DATE FOR BEGINNING OF FULL ICE COVER

     309.000         22.800                  NORMAL

***ICE PARAMETERS FOR PARTIAL ICE COVER CONDITIONS***
```

```
*INDEXES FOR PARTIAL ICE COVER LOADING CASES

1            1            1            0            0            0

*FY ICE THICKNESS

    1.500000

**FY RIDGE PARAMETERS

*COVERAGE (PERCENT)

 0.30000E+02    0.00000E+00    0.00000E+00   DETERMINISTIC

*HEIGHT (M)

 0.90000E+00    0.90000E+00    0.76000E+00   EXPONENTIAL

*LENGTH (M)

 0.15000E+03    0.00000E+00    0.00000E+00   DETERMINISTIC

*VELOCITY (M/S)

 0.42000E-01    0.42000E-01    0.00000E+00   EXPONENTIAL

*FRICTION ANGLE (RAD.)

 0.43633E+00    0.00000E+00    0.00000E+00   DETERMINISTIC

*COHESION (MPA)

 0.35000E-01    0.00000E+00    0.00000E+00   DETERMINISTIC

**LEVEL ICE PARAMETERS

*ICE PRESSURE :AVERAGE ,AND MEAN AND S.D. OF EXTREMAL COMPONENT

 0.300E+00   0.200E+00   0.150E+00

**MY FLOE PARAMETERS

*CONCENTRATION (TENTHS)

 0.20000E+00    0.40000E+00    0.00000E+00   BETA

*VELOCITY (M/S)

 0.62000E-01    0.73000E-01    0.00000E+00   GAMMA

*DIAMETER (KM)

 0.10000E+00    0.15000E+00    0.50000E+00   GAMMA

*THICKNESS (M)

 0.39000E+01    0.16000E+01    0.00000E+00   GAMMA

*PRESSURE (MPA)
```

```
 0.50000E+00    0.50000E+00    0.00000E+00   EXPONENTIAL

*RIDGE COVERAGE (PERCENT)

 0.30000E+02    0.00000E+00    0.00000E+00   DETERMINISTIC

*RIDGE HEIGHT (M)

 0.90000E+00    0.90000E+00    0.00000E+00   EXPONENTIAL

*RIDGE LENGTH (M)

 0.15000E+03    0.00000E+00    0.00000E+00   DETERMINISTIC

*FY ICE PRESSURE (MPA)

 0.50000E-01    0.50000E-01    0.00000E+00   NORMAL

***ICE PARAMETERS FOR OPEN WATER CONDITIONS

*INDEXS FOR OPEN WATER LOADING CASES

0          1          0          0          0

**MY FLOE PARAMETERS

*CONCENTRATION (TENTHS)

 0.40000E+00    0.12000E+01    0.00000E+00   BETA

*VELOCITY (M/S)

 0.17000E+00    0.13000E+00    0.00000E+00   GAMMA

*DIAMETER (KM)

 0.10000E+00    0.15000E+00    0.50000E+00   GAMMA

*THICKNESS (M)

 0.39000E+01    0.16000E+01    0.00000E+00   GAMMA

*PRESSURE (MPA)

 0.50000E+00    0.50000E+00    0.00000E+00   EXPONENTIAL

*RIDGE COVERAGE (PERCENT)

 0.30000E+02    0.00000E+00    0.00000E+00   DETERMINISTIC

*RIDGE HEIGHT (M)

 0.90000E+00    0.90000E+00    0.00000E+00   EXPONENTIAL

*RIDGE LENGTH (M)

 0.15000E+03    0.00000E+00    0.00000E+00   DETERMINISTIC

*CONCENTRATION-VELOCITY CORRELATION COEFF.
```

-.25000

```
                    ****** P R O G R A M   I N P U T *****

                 INTERACTIVE PRE-PROCESSOR FOR PROBABILISTIC

                              ICE LOAD PROGRAM

                DEVELOPED BY DET NORSKE VERITAS (CANADA) LTD.

                           RELEASED MARCH,1988




ENTER RUN TITLE (MAX. 60 CHARACTERS)

DEMONSTARTION


INPUT GEOGRAPHIC AREA

1 = BEAUFORT SEA

2 = GRAND BANKS

3 = OTHER

1


INPUT ICE ZONE

1 = LANDFAST ZONE    2 = PACK ZONE

2


INPUT WATER DEPTH (M)

40


INPUT DISTANCE OFFSHORE (KM)
INPUT TYPE OF STRUCTURE

1 =VERTICAL      2 = CONICAL

1


SHAPE OF STRUCTURE IN PLAN

1 = CIRCULAR      2 = POLYGONAL

1


INPUT STRUCTURAL DIAMETER IN METERS

100




STRUCTURAL GEOMETRY USED IS AS FOLLOWS:


INDEX     PROPERTY                          CURRENTLY USED


 1.       SHAPE                             VERTICAL

 2.       SHAPE IN PLAN                     CIRCULAR

 3.       DIAMETER                           100.00    M


ENTER INDEX OF LINE YOU WISH TO CHANGE (0=NONE)

0



POSSIBLE ICE CONDITIONS (SEASONS) ARE AS FOLLOWS:


 1. OPEN WATER

 2. FULL FIRST YEAR ICE COVER
 3. PARTIAL FIRST YEAR ICE COVER

ENTER 1 (=CONSIDERED) OR (0=NOT CONSIDERED) FOR EACH OPTION

3 ENTRIES EXPECTED

1,0,1



BOUNDARY DATES BETWEEN DIFFERENT ICE CONDITIONS ARE AS FOLLOWS:


INDEX  PARAMETER                     MEAN        STD. DEV. DISTRIBUTION

                                 (DAY/MONTH)     (DAYS)


 1.    BEGIN. OF PARTIAL FY COVER   22/  6         18.10   NORMAL

 2.    BEGIN. OF OPEN WATER          6/  7         22.90   NORMAL

 3.    END OF OPEN WATER             5/ 11         22.80   NORMAL


ENTER INDEX OF LINE YOU WISH TO CHANGE (0=NONE)

0


POSSIBLE LOADING SCENARIOS ARE AS FOLLOWS:


 1. FIRST YEAR RIDGES

 2. FIRST YEAR LEVEL ICE

 3. MULTIYEAR FLOES

 4. ICE BERGS

 5. ICE ISLANDS

 6. ICE ISLAND FRAGMENTS


ENTER 1 (=CONSIDERED) OR 0 (=NOT CONSIDERED) FOR EACH SCENARIO

6 ENTRIES EXPECTED
```

```
1.1.1.0.0,0


THICKNESS OF FY ICE =        1.50        M

DO YOU WISH TO CHANGE

1 = YES         0 = NO

0



PARTIAL ICE COVER FY RIDGE PARAMETERS USED ARE AS FOLLOWS :


INDEX  PARAMETER          UNITS        MEAN   STD. DEV.  DISTRIBUTION


 1.    RIDGE COVERAGE     PERCENT 30.0000        .0000   DETERMINISTIC

 2.    RIDGE HEIGHT       M          .9000       .9000   EXPONENTIAL

 3.    RIDGE LENGTH       M       150.0000       .0000   DETERMINISTIC

 4.    ICE SPEED          M/S        .0420       .0420   EXPONENTIAL

 5.    FRICTION ANGLE     DEG.     25.0000       .0000   DETERMINISTIC

 6.    COHESION           MPA        .0350       .0000   DETERMINISTIC

ENTER INDEX OF PARAMETER YOU WISH TO CHANGE (0=NONE)

LOWER BOUND CAN ALSO BE SET FOR SELECTED PARAMETER

0



PARTIAL ICE COVER LEVEL ICE PARAMETERS USED ARE :


INDEX    PARAMETER                               UNITS      VALUE


 1.      AVERAGE ICE PRESSURE                    MPA        0.30E+00

 2.      MEAN OF EXTREMAL PRESSURE COMPONENT     MPA        0.20E+00
 3.      S.D. OF EXTREMAL PRESSURE COMPONENT     MPA        0.15E+00


ENTER INDEX OF PARAMETER YOU WISH TO CHANGE (0=NONE)

0




PARTIAL ICE COVER MY FLOE PARAMETERS USED ARE AS FOLLOWS :


INDEX  PARAMETER          UNITS       MEAN   STD. DEV.  DISTRIBUTION


 1.    MY CONCENTRATION  TENTHS     .2000       .4000  BETA

 2.    FLOE VELOCITY     M/S        .0620       .0700  GAMMA

 3.    FLOE DIAMETER     KM         .1000       .1500  GAMMA

 4.    FLOE THICKNESS    M         3.9000      1.6000  GAMMA

 5.    ICE PRESSURE      MPA        .5000       .5000  EXPONENTIAL

 6.    MY RIDGE COVERAGE PERCENT 30.0000       .0000  DETERMINISTIC

 7.    MY RIDGE HEIGHT   M          .9000       .9000  EXPONENTIAL

 8.    MY RIDGE LENGTH   M       . 150.0000     .0000  DETERMINISTIC

 9.    FY ICE PRESSURE   MPA        .0500       .0500  NORMAL


ENTER INDEX OF PARAMETER YOU WISH TO CHANGE (0=NONE)

LOWER BOUND CAN ALSO BE SET FOR SELECTED PARAMETER

0



POSSIBLE LODING SCENARIOS ARE AS FOLLOWS:


 1. FIRST YEAR FLOES

 2. MULTIYEAR FLOES

 3. ICE BERGS

 4. ICE ISLANDS
 5. ICE ISLAND FRAGMENTS


ENTER 1 (=CONSIDERED) OR 0 (=NOT CONSIDERED) FOR EACH SCENARIO

5 ENTRIES EXPECTED

0,1,0,0,0


ENTER DEFAULT OPTION FOR MULTIYEAR FLOES :

1 = PROGRAM DEFAULT

2 = USER VALUES AS DEFINED FOR PREVIOUS SEASONS

1




OPEN WATER MY FLOE PARAMETERS USED ARE AS FOLLOWS :


INDEX  PARAMETER          UNITS       MEAN    STD. DEV.  DISTRIBUTION


 1.    MY CONCENTRATION  TENTHS      .4000      1.2000   BETA

 2.    FLOE VELOCITY     M/S         .1700       .1300   GAMMA

 3.    FLOE DIAMETER     KM          .1000       .1500   GAMMA

 4.    FLOE THICKNESS    M          3.9000      1.6000   GAMMA

 5.    ICE PRESSURE      MPA         .5000       .5000   EXPONENTIAL

 6.    MY RIDGE COVERAGE PERCENT 30.0000       .0000   DETERMINISTIC

 7.    MY RIDGE HEIGHT   M           .9000       .9000   EXPONENTIAL

 8.    MY RIDGE LENGTH   M        150.0000       .0000   DETERMINISTIC


ENTER INDEX OF PARAMETER YOU WISH TO CHANGE (0=NONE)

LOWER BOUND CAN ALSO BE SET FOR SELECTED PARAMETER

0
```

```
CORRELATION COEF. FOR ICE CONCENTRATION AND ICE VELOCITY = -.250

DO YOU WISH TO CHANGE

1 = YES        0 = NO

0
```

```
                 ***** P R O G R A M   M A I N *****

         PROBABILISTIC ASSESSMENT OF YEAR-ROUND ICE LOADS ON

              FIXED STRUCTURES IN THE CANADIAN OFFSHORE

             DEVELOPED BY DET NORSKE VERITAS (CANADA) LTD.

                        RELEASED MARCH, 1988




RUN TITLE : DEMONSTRATION

=========




I/O FILE NAMES :

==============


  DATA BASE FILE :  DBTEST

  INPUT FILE     :  INTESTR

  DUMP FILE      :  DUTESTR




STATISTICAL PARAMETERS :

======================


  TOLERANCE FOR MEAN FORCE =   0.25E-01

  BIN WIDTH FOR FORCE PDF  =      10.00  MN
```

```
PARTIAL ICE COVER SEASON :
========================

  AVERAGE SEASON LENGTH =   20.  DAYS


  FIRST YEAR RIDGES :

    AVERAGE INTERACTION RATE        =   0.44E+03  PER SEASON
    NUMBER OF SIMULATIONS           =         33

    FORCE DISTRIBUTION PARAMETERS :

      FORCE                              MEAN (MN)         S.D. (MN)

      FOR ONE COLLISION                    25.25             25.94
      EXTREMAL                            115.00               .05


  FIRST YEAR LEVEL ICE :


    SEASON EXTREME FORCE (MN) :
      MEAN      =     74.00  MN
      STD. DEV. =     23.64  MN
  MULTIYEAR FLOE COLLISIONS :


    AVERAGE COLLISION RATE          =    0.16E+01  PER SEASON

    NUMBER OF SIMULATIONS           =          42


    FORCE DISTRIBUTION PARAMETERS :


      FORCE                              MEAN (MN)          S.D. (MN)


      FOR ONE COLLISION                     56.66              56.55

      EXTREMAL                              62.34              66.38





OPEN WATER SEASON :
=================


  AVERAGE SEASON LENGTH =  122.  DAYS



  MULTIYEAR FLOE COLLISIONS :


    AVERAGE COLLISION RATE          =    0.27E+02  PER SEASON

    NUMBER OF SIMULATIONS           =          31


    FORCE DISTRIBUTION PARAMETERS :


      FORCE                              MEAN (MN)          S.D. (MN)
```

FOR ONE COLLISION	60.92	78.06
EXTREMAL	290.28	72.48

```
                    ***** P R O G R A M   M A I N *****

             PROBABILISTIC ASSESSMENT OF YEAR-ROUND ICE LOADS ON

                 FIXED STRUCTURES IN THE CANADIAN OFFSHORE

                DEVELOPED BY DET NORSKE VERITAS (CANADA) LTD.

                           RELEASED MARCH, 1988




PART ICE COVER

MULTIYEAR FLOES


FY THK     YM THK     FLO DIAM  VELOCITY  ECCEN.     APR AGLE  FY PRESS  MY
 PRESS   FORCE
M          M          KM        M/S       M          RAD.      MPA       MP
A        MN




OPEN WATER

MULTIYEAR FLOES


FY THK     YM THK     FLO DIAM  VELOCITY  ECCEN.     APR AGLE  FY PRESS  MY
 PRESS   FORCE
M          M          KM        M/S       M          RAD.      MPA       MP
A        MN
```

```
.000E+00  .195E+01  .975E+00  .808E+00  .210E+02  .000E+00  .000E+00  .5
67E-02  .111E+01
.000E+00  .631E+01  .975E+00  .135E+00  .284E+03  .000E+00  .000E+00  .6
52E+00  .754E+02
.000E+00  .517E+01  .975E+00  .135E+00  .347E+03  .000E+00  .000E+00  .2
77E+01  .156E+03
.000E+00  .117E+02  .975E+00  .135E+00  .301E+03  .000E+00  .000E+00  .5
56E+00  .124E+03
.000E+00  .440E+01  .975E+00  .135E+00  .250E+02  .000E+00  .000E+00  .3
69E+00  .384E+02
.000E+00  .195E-01  .975E+00  .135E+00  .288E+03  .000E+00  .000E+00  .1
62E+01  .427E+02
.000E+00  .258E+01  .975E+00  .135E+00  .434E+03  .000E+00  .000E+00  .3
63E-01  .392E+01
.000E+00  .195E+01  .975E+00  .135E+00  .611E+02  .000E+00  .000E+00  .4
45E+00  .193E+02
.000E+00  .585E+01  .975E+00  .135E+00  .203E+03  .000E+00  .000E+00  .3
20E+00  .450E+02
.000E+00  .109E+02  .975E+00  .808E+00  .290E+03  .000E+00  .000E+00  .4
85E+00  .337E+03
.000E+00  .195E+01  .975E+00  .135E+00  .313E+03  .000E+00  .000E+00  .1
29E+00  .775E+01
.000E+00  .242E+01  .975E+00  .135E+00  .207E+03  .000E+00  .000E+00  .3
14E+00  .183E+02
.000E+00  .585E+01  .975E+00  .135E+00  .700E+02  .000E+00  .000E+00  .1
37E+01  .123E+03
.000E+00  .113E+02  .975E+00  .135E+00  .373E+03  .000E+00  .000E+00  .2
76E-01  .151E+02
.000E+00  .195E+01  .975E+00  .404E+00  .438E+03  .000E+00  .000E+00  .2
```

```
74E-00   .236E+02
.000E+00   .585E+01   .975E+00   .135E+00   .637E+02   .000E+00   .000E+00   .1
17E+01   .110E+03
.000E+00   .195E+01   .975E+00   .135E+00   .388E+03   .000E+00   .000E+00   .6
34E+00   .213E+02
.000E+00   .195E+01   .975E+00   .404E+00   .453E+03   .000E+00   .000E+00   .1
37E+00   .144E+02
.000E+00   .195E+01   .975E+00   .404E+00   .244E+03   .000E+00   .000E+00   .6
95E-01   .104E+02
.000E+00   .195E+01   .975E+00   .135E+00   .981E+02   .000E+00   .000E+00   .3
87E+00   .175E+02
.000E+00   .585E+01   .975E+00   .404E+00   .390E+03   .000E+00   .000E+00   .1
93E-01   .109E+02
.000E+00   .585E+01   .975E+00   .404E+00   .234E+02   .000E+00   .000E+00   .3
19E+00   .944E+02
.000E+00   .585E+01   .975E+00   .135E+00   .895E+02   .000E+00   .000E+00   .4
53E+00   .583E+02
.000E+00   .195E+01   .975E+00   .135E+00   .228E+03   .000E+00   .000E+00   .5
45E-01   .451E+01
.000E+00   .794E+01   .195E+01   .135E+00   .470E+03   .000E+00   .000E+00   .1
54E+00   .584E+02
.000E+00   .616E+01   .975E+00   .808E+00   .135E+03   .000E+00   .000E+00   .8
49E+00   .297E+03
.000E+00   .195E+01   .975E+00   .808E+00   .407E+03   .000E+00   .000E+00   .4
32E+00   .514E+02
.000E+00   .312E+01   .975E+00   .135E+00   .179E+03   .000E+00   .000E+00   .3
19E+00   .241E+02
.000E+00   .195E+01   .975E+00   .808E+00   .275E+02   .000E+00   .000E+00   .2
27E+00   .372E+02
.000E+00   .195E+01   .975E+00   .135E+00   .400E+03   .000E+00   .000E+00   .8
```

```
77E+00   .261E+02

.000E+00   .585E+01   .975E+00   .135E+00   .472E+03   .000E+00   .000E+00   .1

56E+00   .226E+02
```